Searching for the Higgs at CDF

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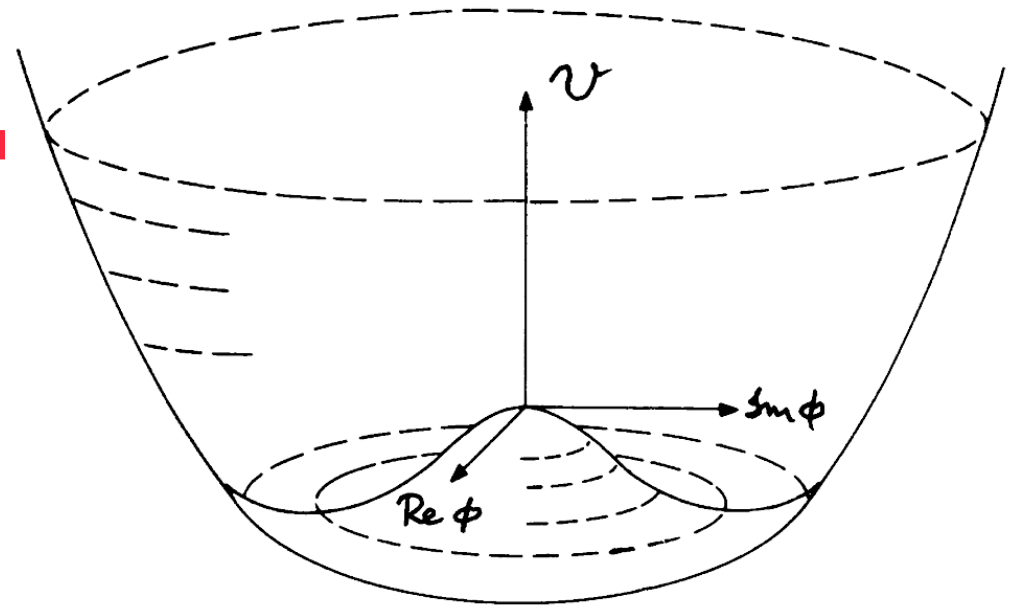
$$\mathcal{L} = (D^\mu \phi)^* D_\mu \phi - V(\phi) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

$$D_\mu \phi = \partial_\mu \phi - ie A_\mu \phi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Contents



- The Tevatron and CDF
- The cross section challenge
- The experimental challenge

- Searches for Standard Model Higgs boson
  - m_H < ~135 GeV/c^2: *WH*, *ZH* associated production
  - m_H > ~135 GeV/c^2: *WW* final state

- Beyond the Standard Model Higgs

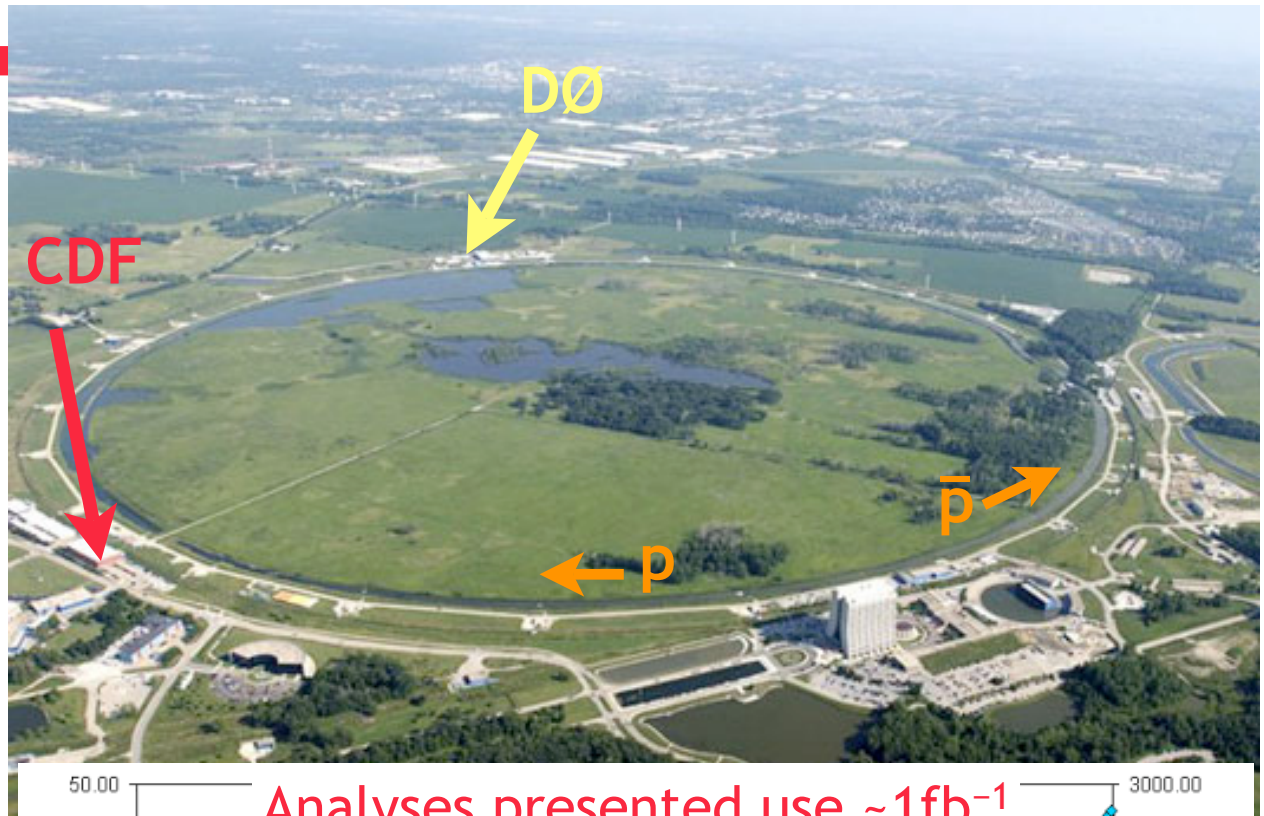
- Summary and Outlook

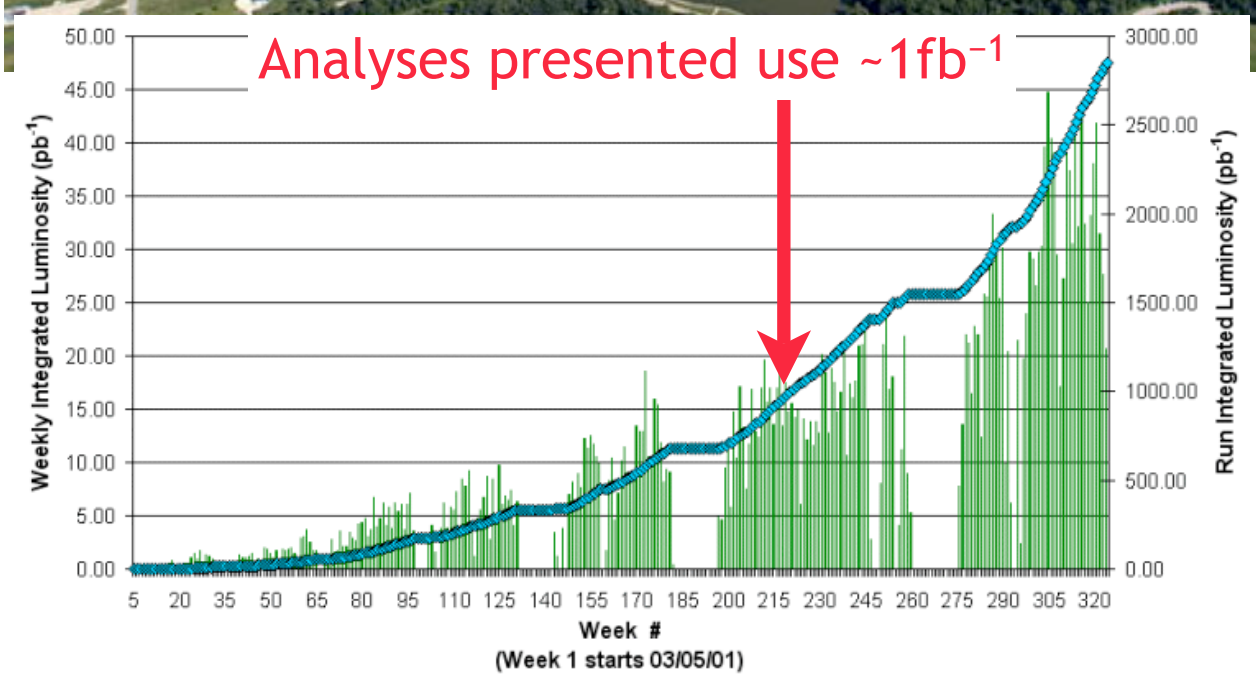
The Tevatron

- World's highest energy (operating) collider
- p $\bar{p}$ at E_{CM} = 1.96 TeV
- $\mathcal{L}$(peak) = 2.8×10^{32} cm^{-2}s^{-1}

- Key parameter $N = \sigma \cdot \int \mathcal{L} dt$

- $\int \mathcal{L} dt$ delivered ~2.9fb^{-1}
- CDF data taking efficiency >80%

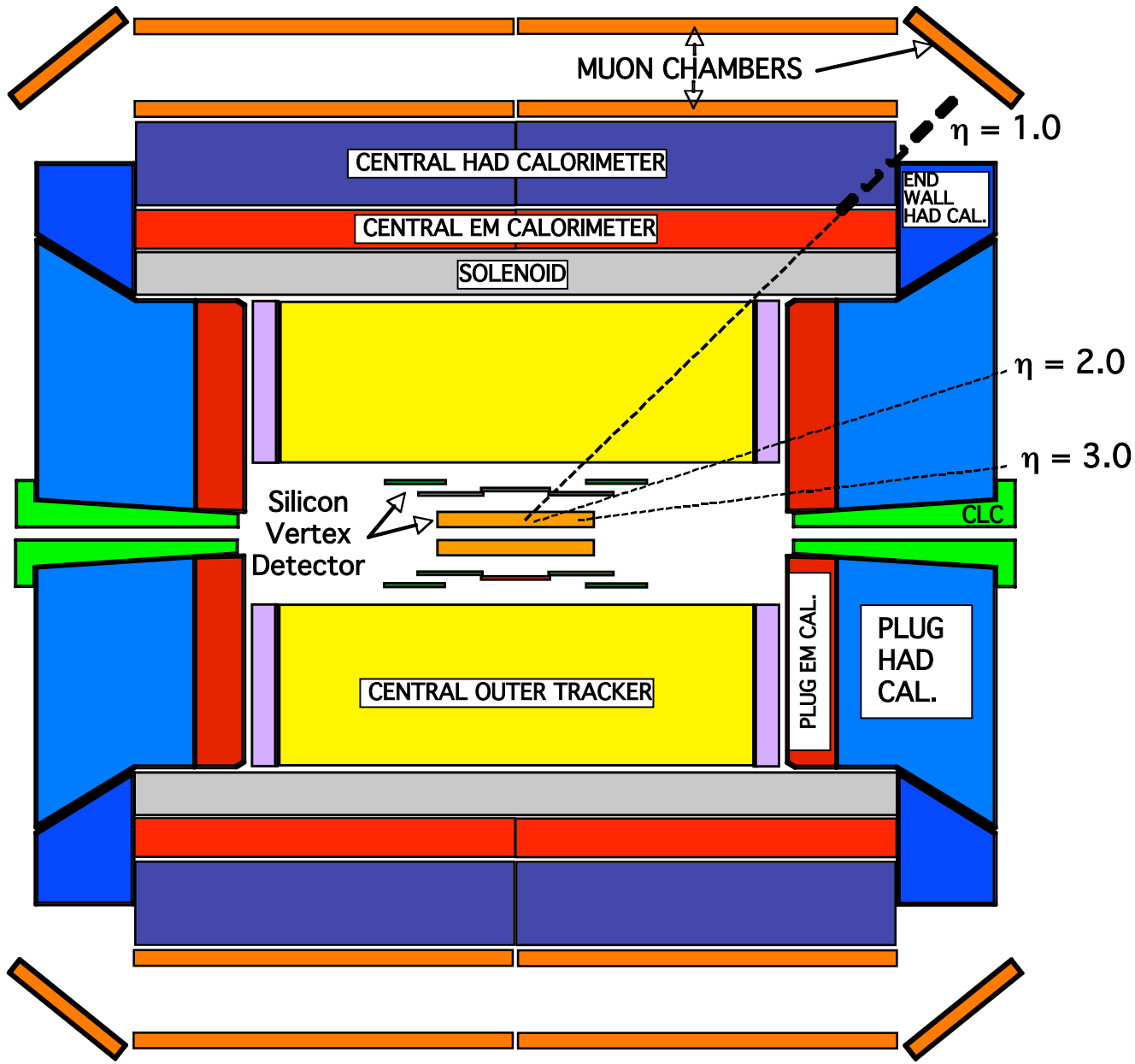




CDF

Pseudorapidity
$\eta = -\ln \tan(\theta/2)$

- General Purpose Collider Experiment



CDF

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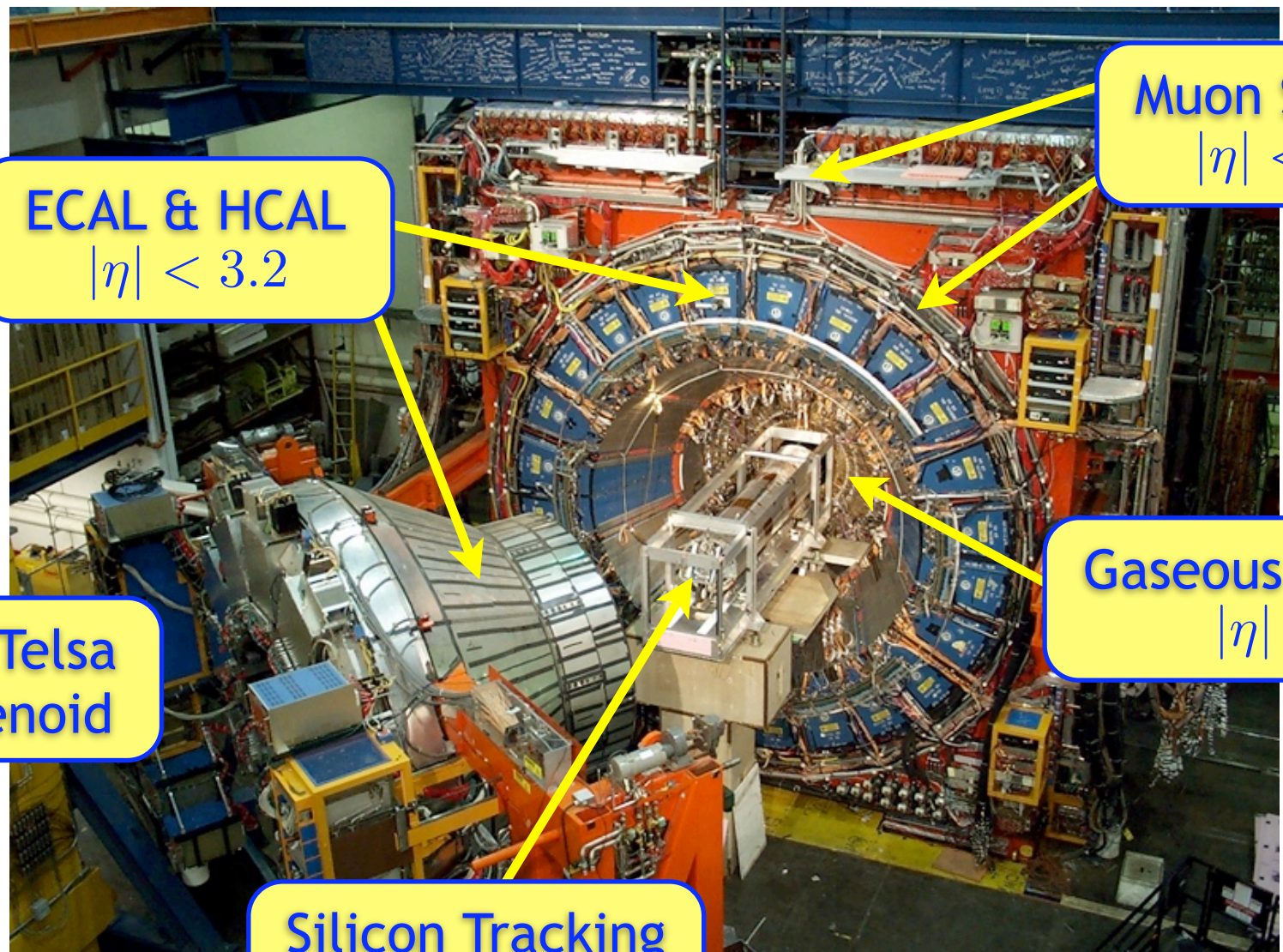
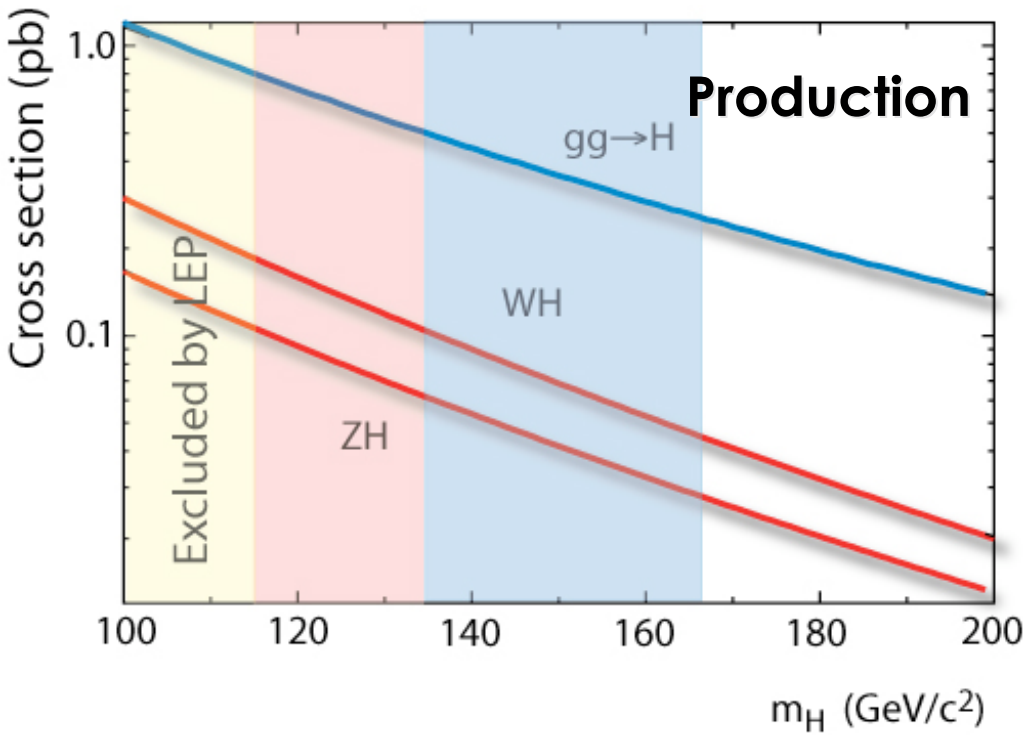
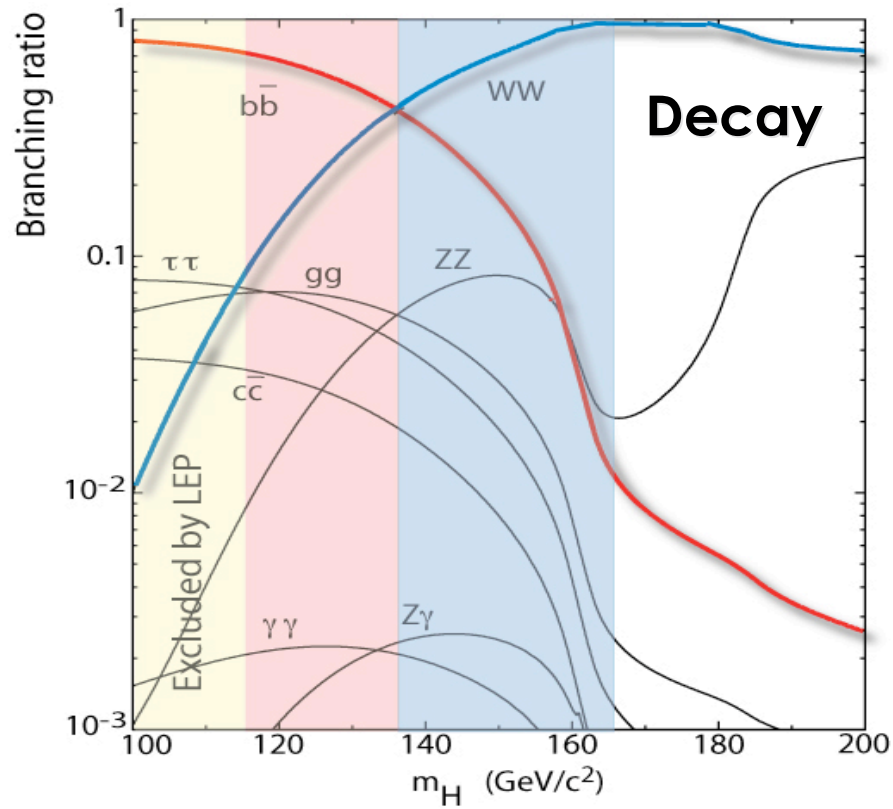


The Cross Section Challenge

Higgs at the Tevatron





Most sensitive Tevatron searches

If Higgs is low mass, m_H<135 GeV/c^2:

- Produced with *W* or *Z* boson
- Decay to *b*-quark pair

$WH \to \ell\nu b\bar{b}$ $ZH \to \ell^+\ell^- b\bar{b}$ $ZH \to \nu\bar{\nu} b\bar{b}$

If Higgs is high mass, m_H>135 GeV/c^2:

- Direct production gg→H
- Decay to a *W*-boson pair

$gg \to H \to WW^*$

Indirect Searches

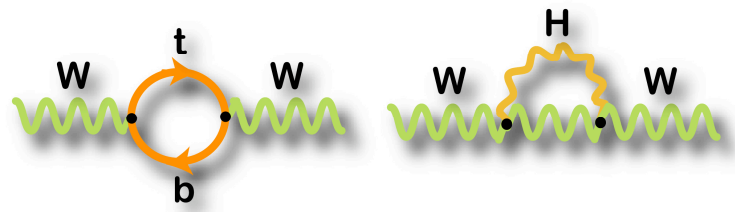
Indirect Searches

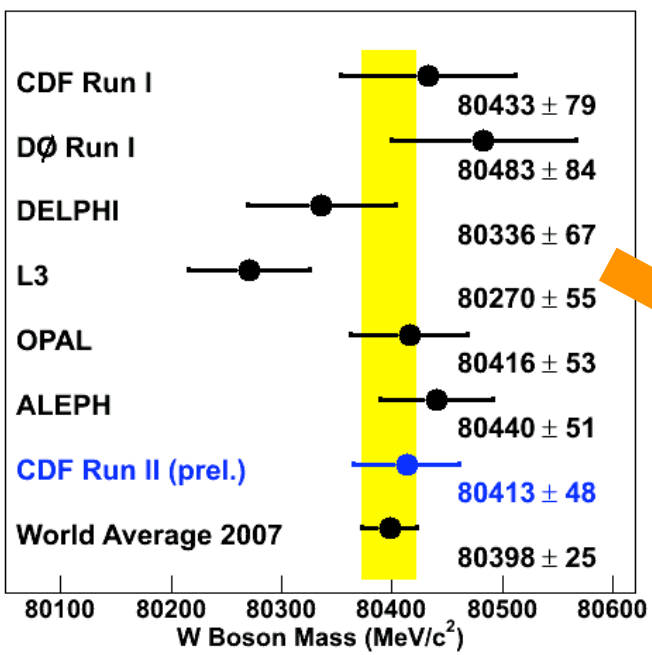
If you believe in the Standard Model...

Indirect Searches

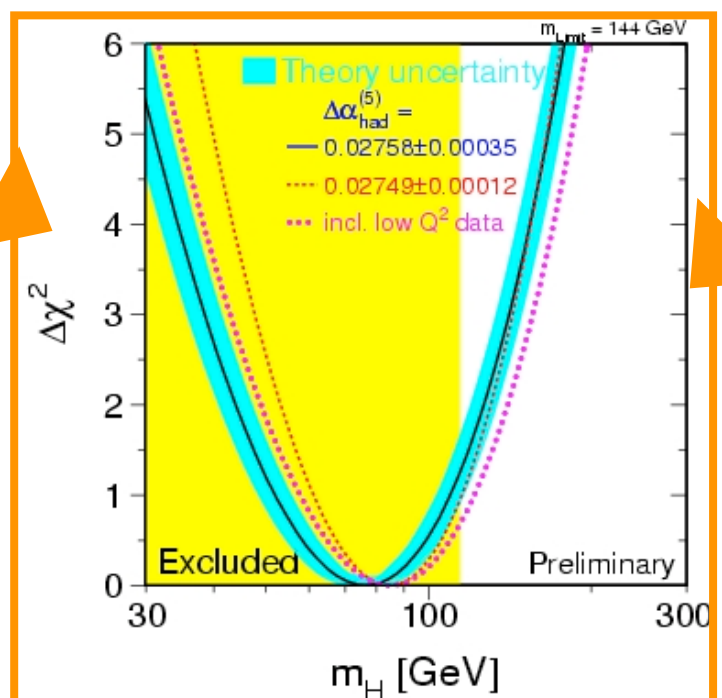
If you believe in the Standard Model...

Tevatron data already contributes to most stringent constraint on m_H through radiative corrections

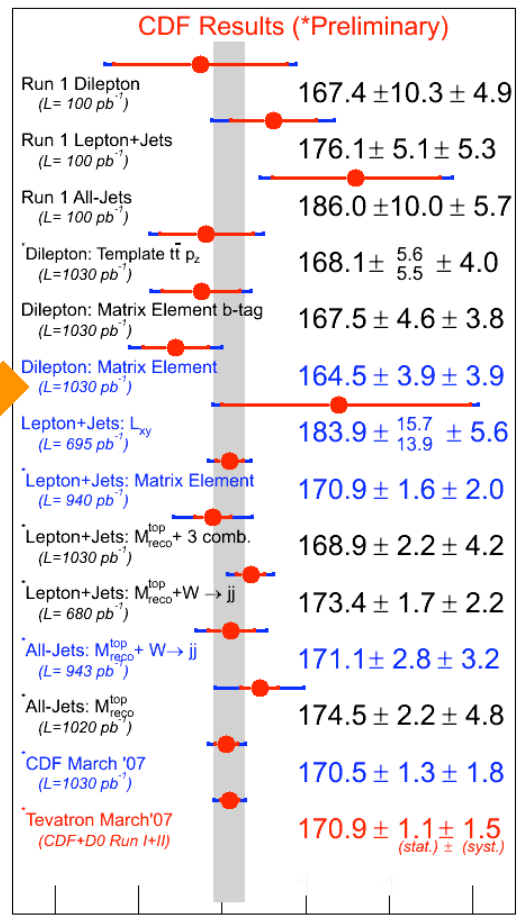




M_W = 80413 ± 48 MeV/c^2



m_H < 182 GeV/c^2 at 95% CL



$M_t^{(CDF)}$ = 170.9 ± 1.1(stat) ± 1.5(syst) GeV/c^2

The Experimental Challenge

The Experimental Challenge

Finding the Higgs at the Tevatron is **possible!** But very **challenging.**

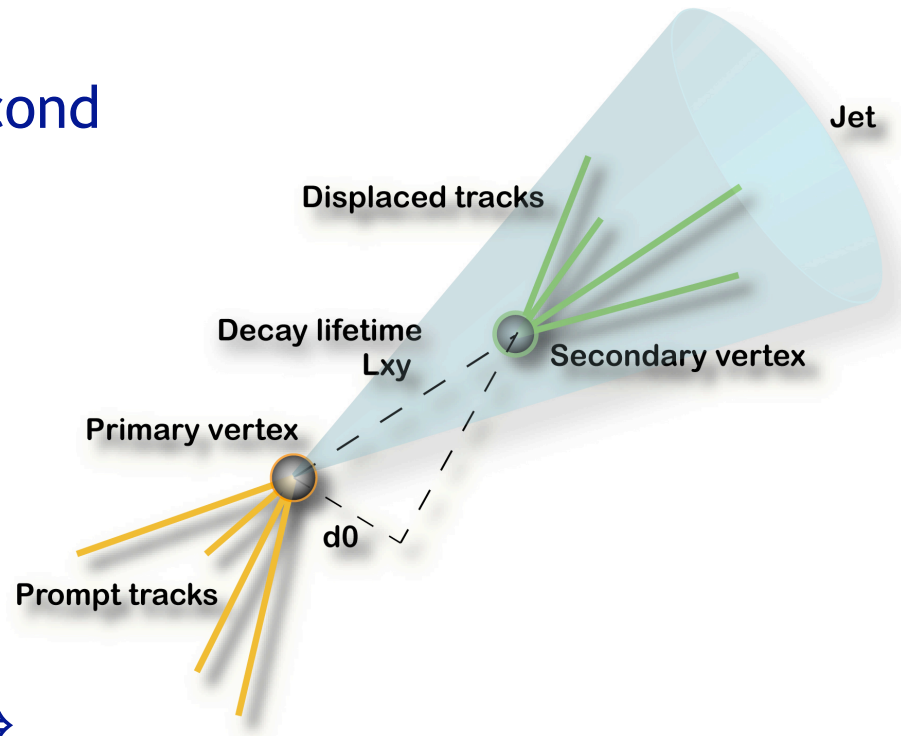
Low Higgs production cross section and large backgrounds.

Typical events in $1fb^{-1}$ (ℓ=e,μ)	$ZH \to \ell\ell b\bar{b}$	$ZH \to \nu\bar{\nu} b\bar{b}$	$WH \to \ell\nu b\bar{b}$	$H \to WW^* \to \ell\nu\ell\nu$
Signal produced	5	15	30	20
Signal Accepted	1	2	3	4
Backgrounds	100	300	500	300

1. Improve signal acceptances:
   - Use all detector nooks & crannies, improve triggers & *b*-tagging efficiencies
2. Reduce backgrounds:
   - Improve *b*-tagging algorithms, di-jet mass resolution
3. Use sophisticated analysis techniques to extract signal from background:
   - Multivariate techniques, neural networks, matrix elements, ...
4. Combine all channels, and both experiments
5. Collect and analyse as much luminosity as possible

b-tagging at CDF

- For $m_H < 135$ GeV/c^2, *b*-jet tagging is **crucial**
- **Secondary vertex tagging** identifies second vertices in jet
  - identifies 40–50% of *b*-quark jets
  - tags 0.5–1% light quark jets (*u*,*d*,*s*)
    - ➡ "fake rate"
- A neural net can be used to refine tag ⇒ improve *b*-jet purity

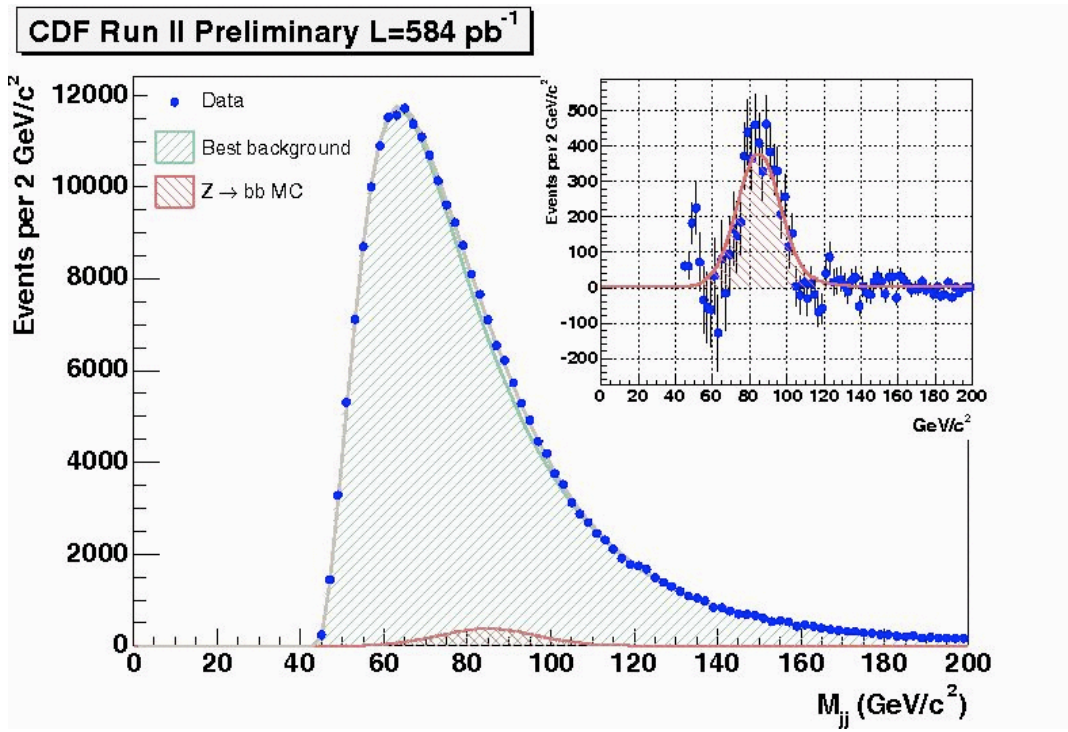


- **One *b*-tag** improves signal to background improves from 1:1000 to 1:100
- **Two *b*-tags** improves signal to background of 1:50

Di-jet mass resolution

Dedicated work to understand the response of calorimeter to *b*-jets.

- $Z \rightarrow b\bar{b}$ events used to calibrate *b*-jet response.
- Sample: two tagged *b*-jets.
- **Dedicated trigger** employed.
- Background template from data



$N(Z \rightarrow b\bar{b}) = 5674 \pm 448$ (stat)

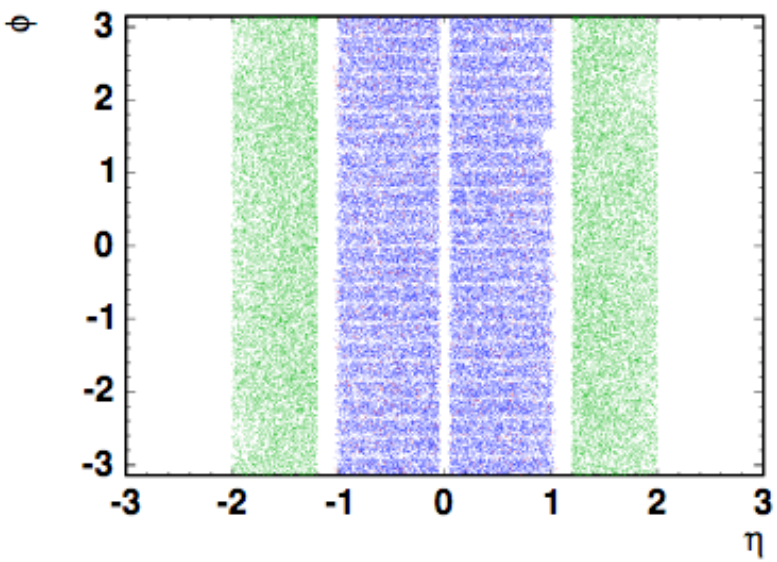
Energy scale factor for *b*-jets:

$k = 0.974 \pm 0.011(\text{stat})\ ^{+0.017}_{-0.014}$ (syst)

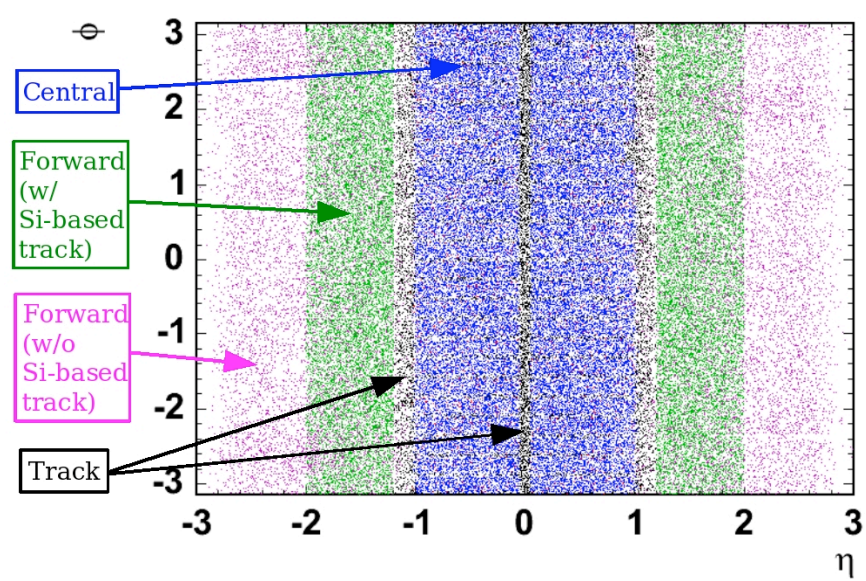
Lepton Acceptance

- Leptons are critical for the H→*WW** search
- Vast improvement in identifying leptons by understanding the "holes" in the calorimetry and muon chamber acceptance.

Electrons before



Electrons after

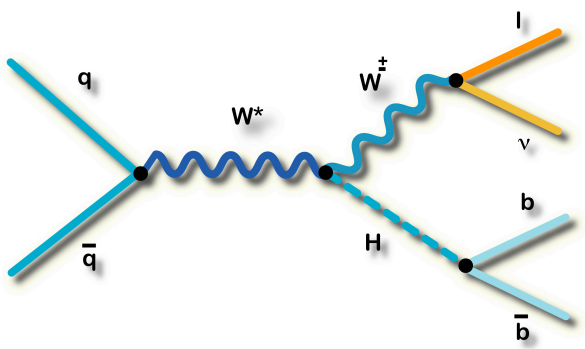


- At m_H=160 GeV/c^2 signal yield increases from **2.5 to 4** expected events

Low Mass Higgs Searches

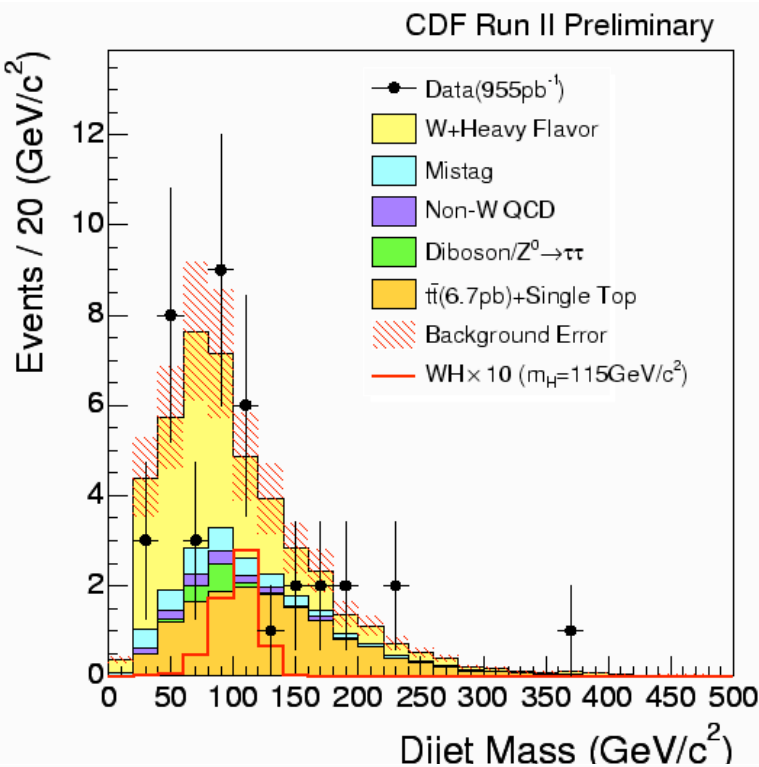
- m_H < ~135 GeV/c^2
- $WH \rightarrow \ell \nu b\bar{b}$ $ZH \rightarrow \ell^+\ell^- b\bar{b}$ $ZH \rightarrow \nu\,\bar{\nu}\, b\bar{b}$

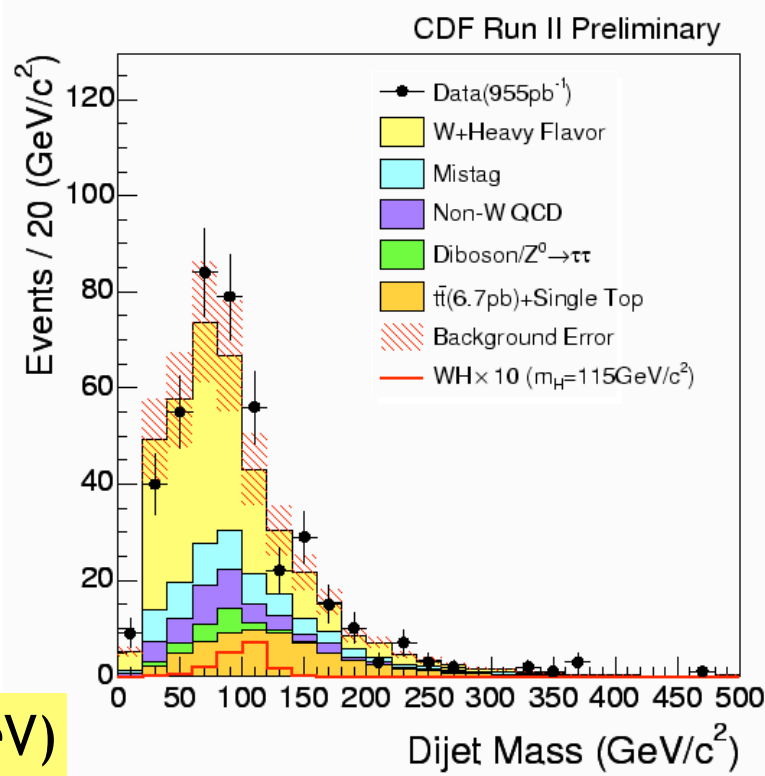
Higgs Search: $WH \rightarrow \ell\nu\, b\bar{b}$



- Signal selection:
  - high-p_T, isolated, electron or muon
    - ➡ $p_T(\ell) > 20$ GeV/c
  - Two high-E_T central jets: E_T(jet) > 20 GeV
    - ➡ 1 or 2 b-tags
  - Large $\not\!\!E_T$: $\not\!\!E_T > 20$ GeV
- Backgrounds:
  - W+heavy flavour production
  - top pair production

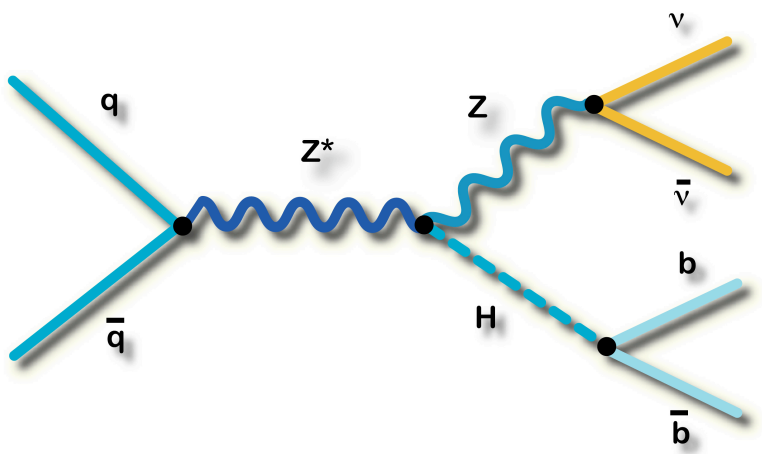
➡ **Look for resonant peak in di-jet mass**

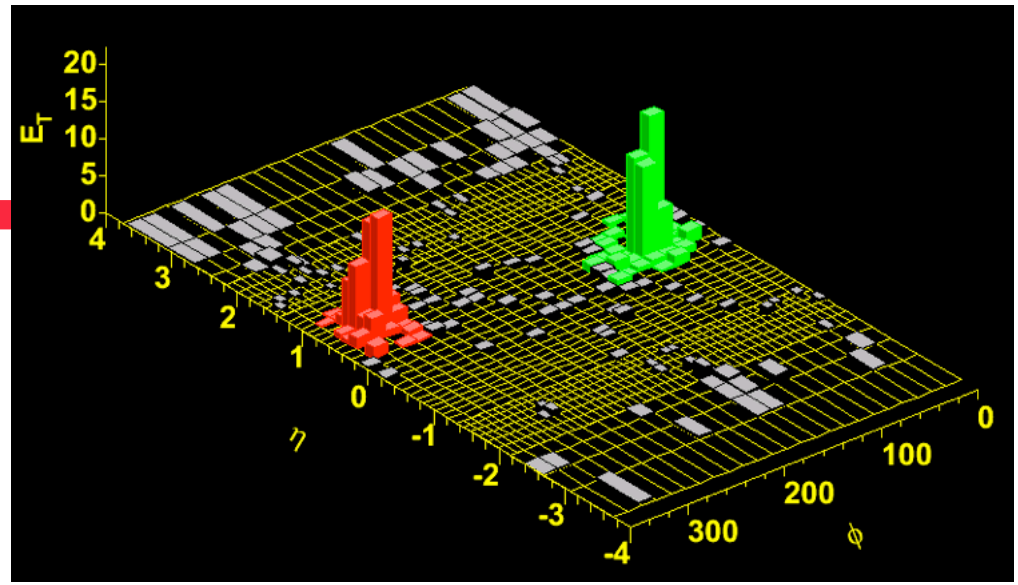




Limit: σ(observed)/σ(SM) < 26 (for m_H=115 GeV)

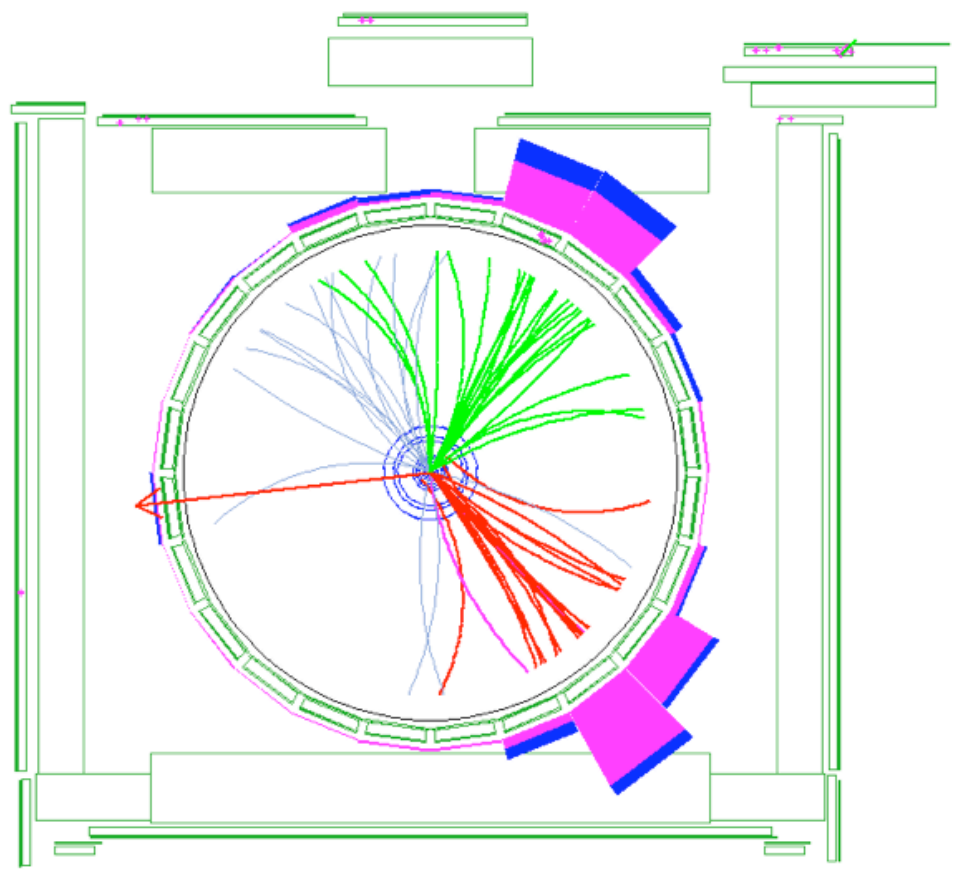
$ZH \to \nu\bar{\nu}\, b\bar{b}$



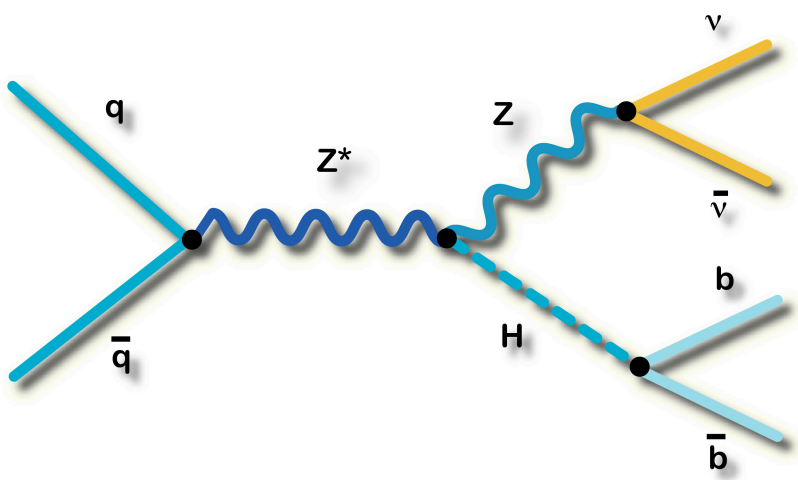


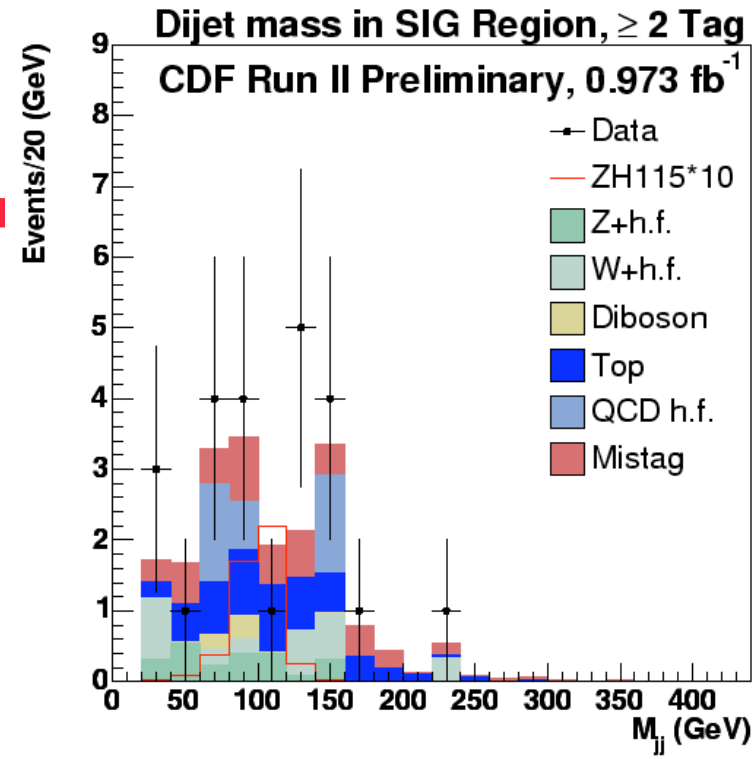
- Signature:
  - 2 high-E_T jets with 1 or 2 *b*-tags
  - large $\not\!\!E_T$
  - no isolated leptons
- Huge background from QCD jet production: optimised cuts imposed

$$\begin{aligned} \not\!\!E_T &> 75\ \text{GeV} \\ E_T(j^1) &> 60\ \text{GeV} \\ \Delta\phi(j^1, \not\!\!E_T) &> 0.8 \end{aligned}$$



$ZH \rightarrow \nu\bar{\nu}\, b\bar{b}$



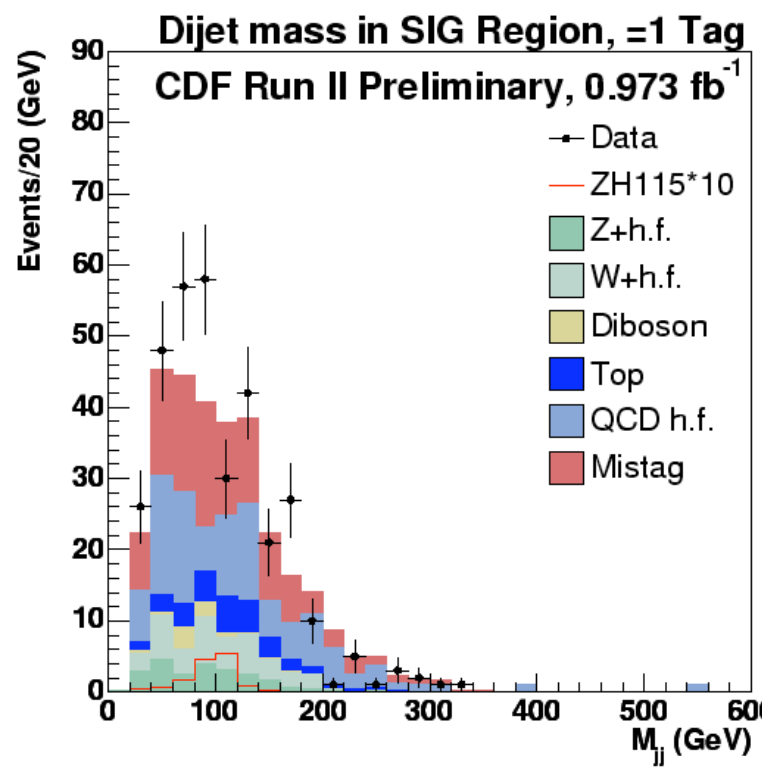


Main backgrounds:

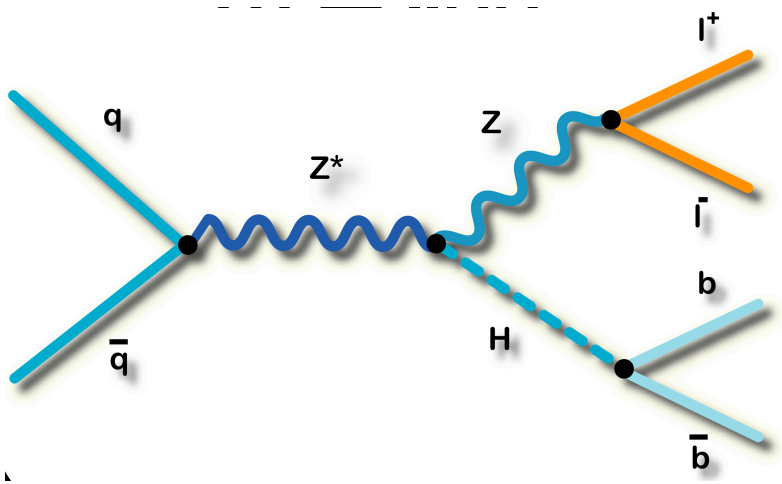
- Residual QCD multi-jet production
- Mistags: light jet tagged as *b*-jet
- Top quark production

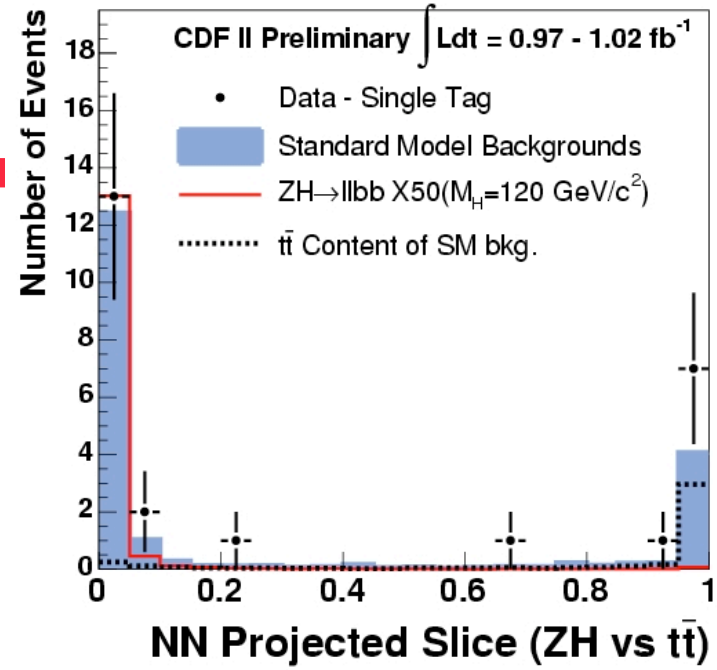
- **No significant resonance observed in di-jet mass peak**

Observed Limit: $\sigma(ZH \rightarrow \nu\bar{\nu}\, b\bar{b}) < 15\ \sigma(SM)$

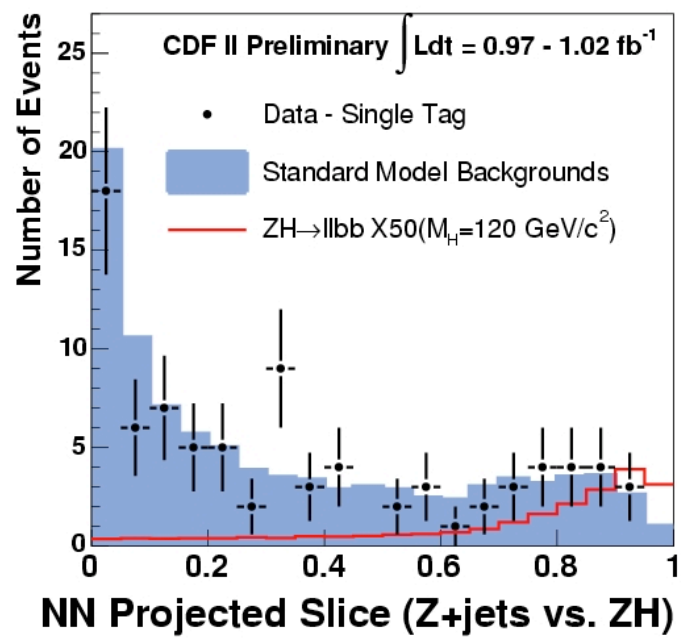


$ZH \rightarrow \ell^+\ell^- b\bar{b}$





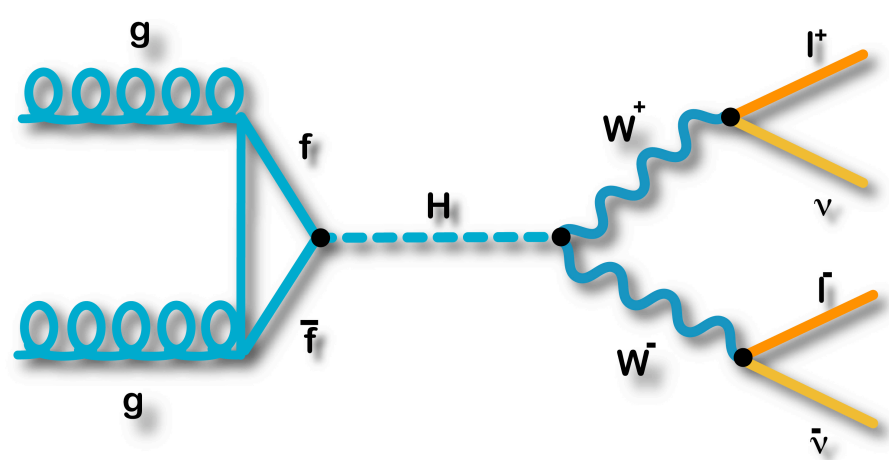
- 2 leptons and 2 jets (1 or 2 tagged as *b*-jets)
- ~100 events pass cuts; only 1 expected to be from SM Higgs production
- Use 2D NN to separate signal from backgrounds:
  - 1 NN tuned to find $t\bar{t}$
  - 1 NN tuned to find *ZH*
- **NN^2 technique improves sensitivity by 2.5**



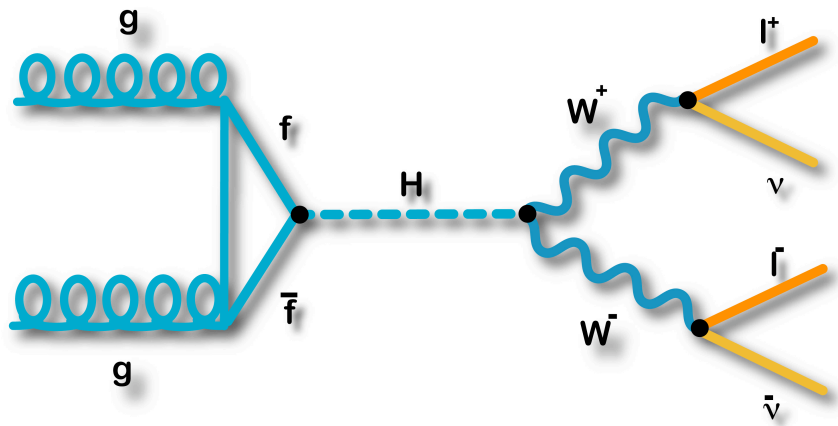
Limit: $\sigma(\text{observed})/\sigma(SM) < 16$ (for m_H=115 GeV)

Higher Mass Higgs Searches

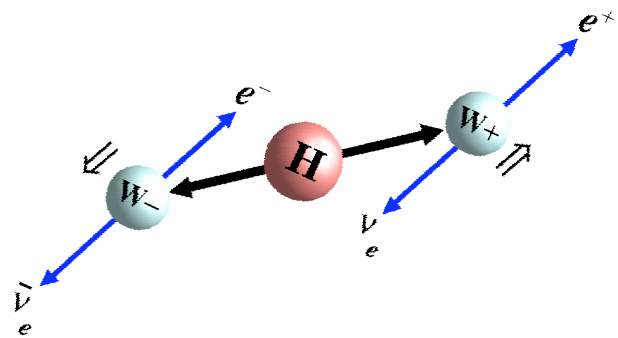
- m_H > ~ 135 GeV/c^2



$H \rightarrow WW^* \rightarrow \ell^+\ell^-\nu\bar{\nu}$

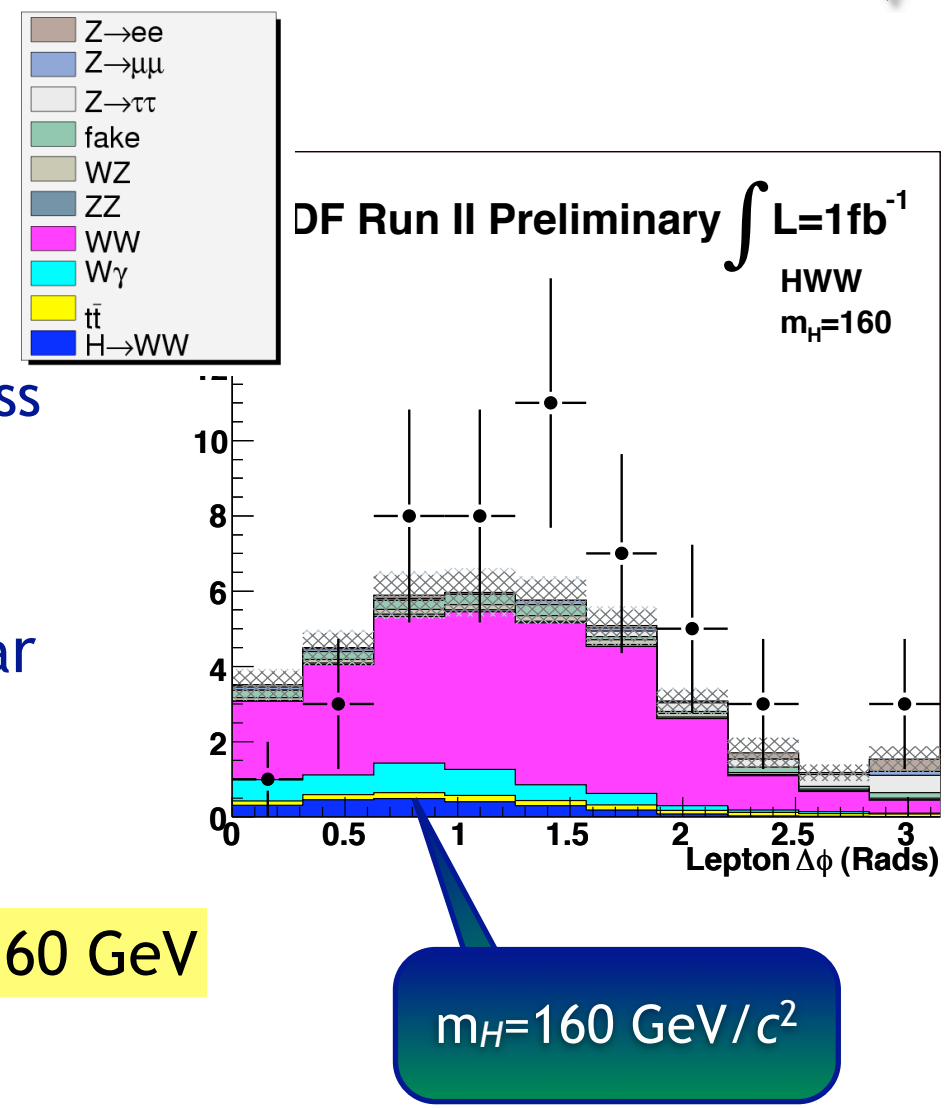


- Reconstruction of Higgs mass impossible due to two neutrinos in the final state



- Make use of spin correlations to suppress *WW* background:
  - Higgs has spin=0

  ➡ leptons from Higgs decay are collinear
- Look for peak in Δϕ between leptons



Limit: σ(observed)/σ(SM) < 10 for m_H=160 GeV

m_H=160 GeV/c^2

$H \rightarrow WW^*$ Matrix Element Method

- Probability density to observe given leptons and $\not\!\!E_T$:

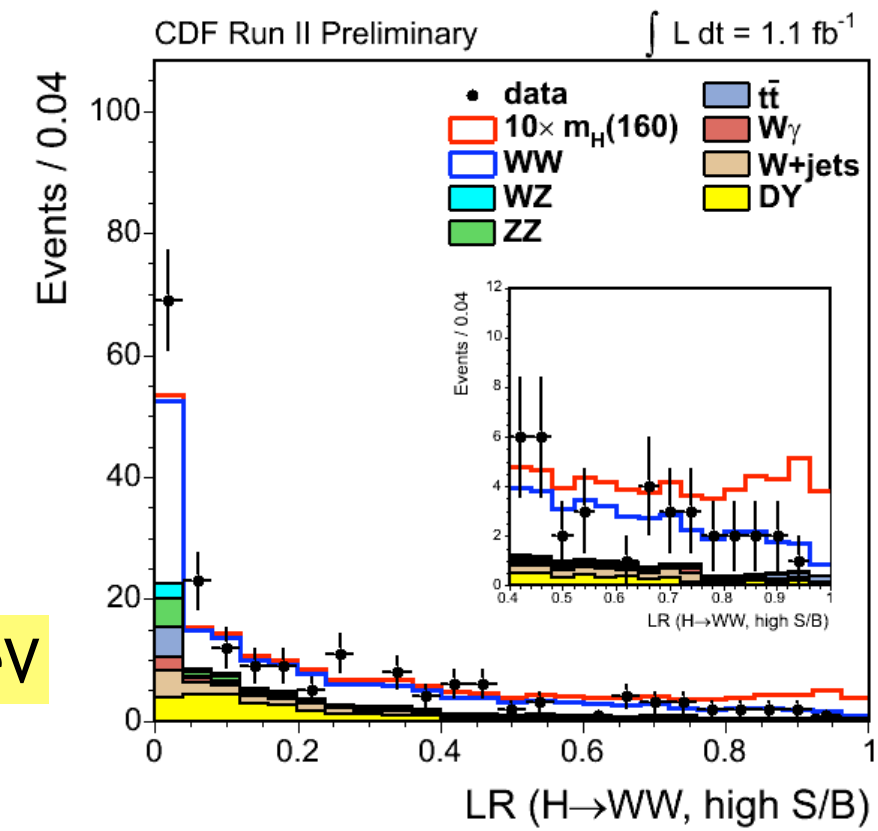
$$P(\vec{x}_{\rm obs}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{\rm th}(y)}{dy} \epsilon(y)\, G(\vec{x}_{\rm obs}, y)\, dy$$

observed lepton info — efficiency — resolution — true lepton info

- Define Likelihood Ratio:

$$\mathrm{LR}(\vec{x}_{\rm obs}) = \frac{P_H(\vec{x}_{\rm obs})}{P_H(\vec{x}_{\rm obs}) + \Sigma_{\rm backg}\, k_i\, P_i(\vec{x}_{\rm obs})}$$

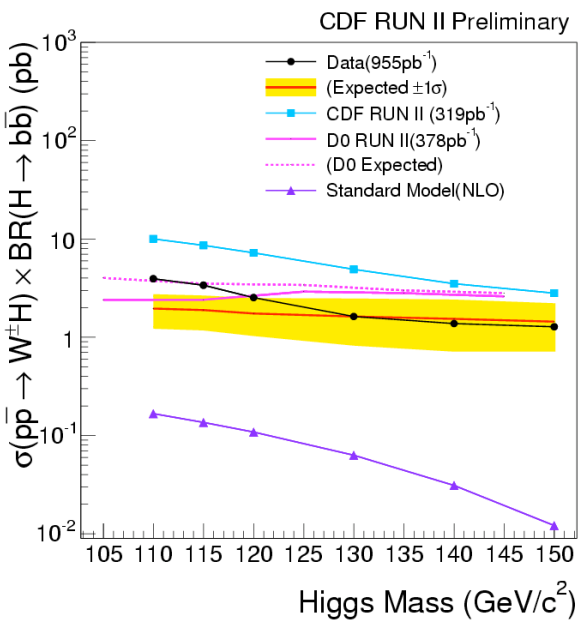
- Gives most discriminatory power between background and signal



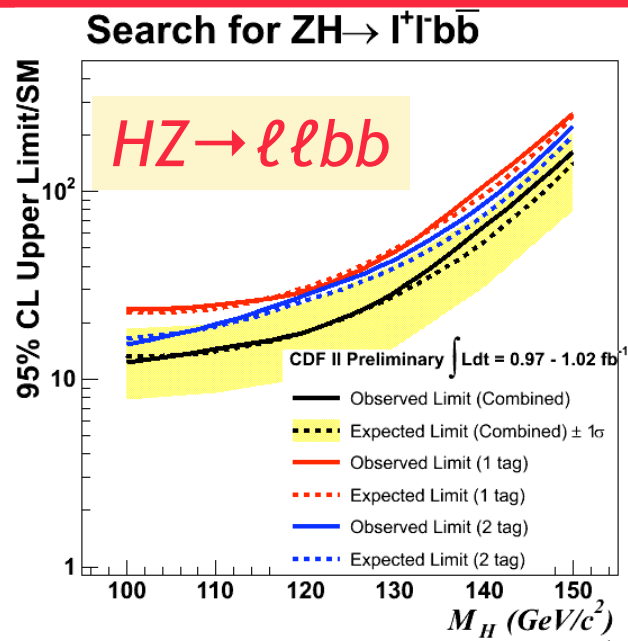
Limit: σ(obsv)/σ(SM) < 3.5 for m_H=160 GeV

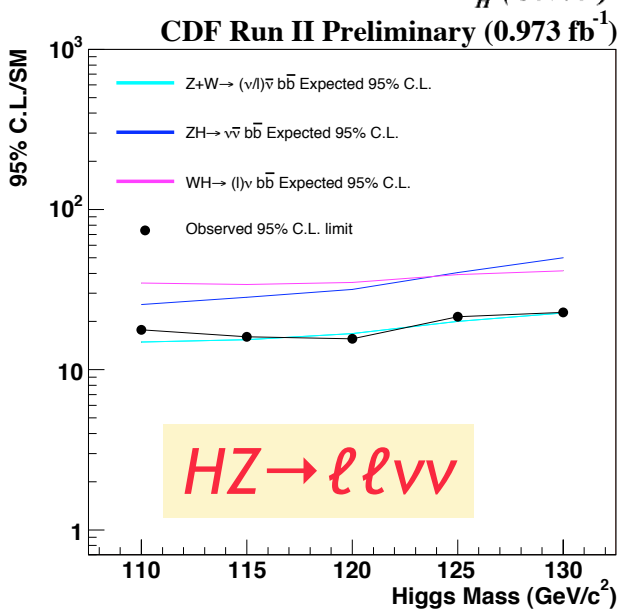
SM Higgs Exclusion Plots

$WH \rightarrow \ell\nu bb$

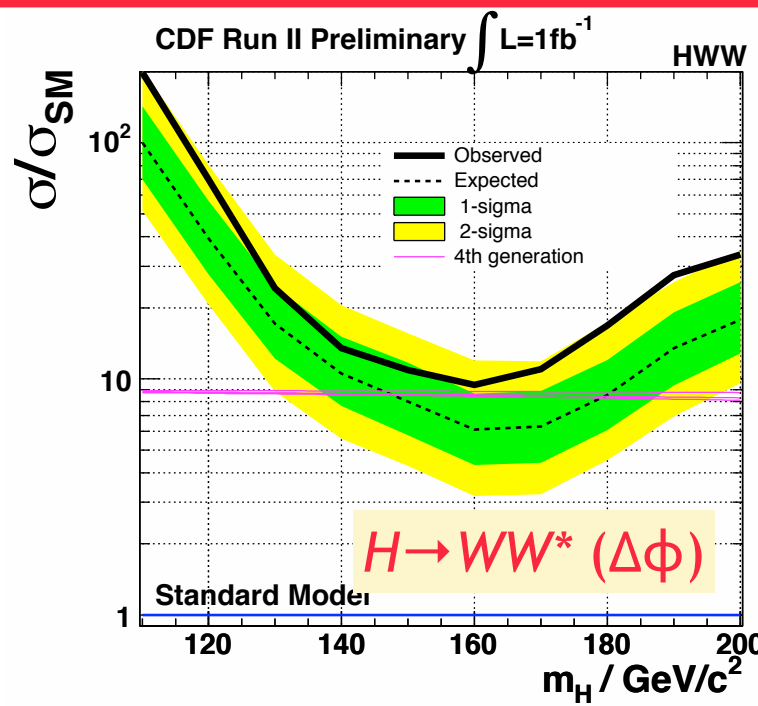


$HZ \rightarrow \ell\ell bb$



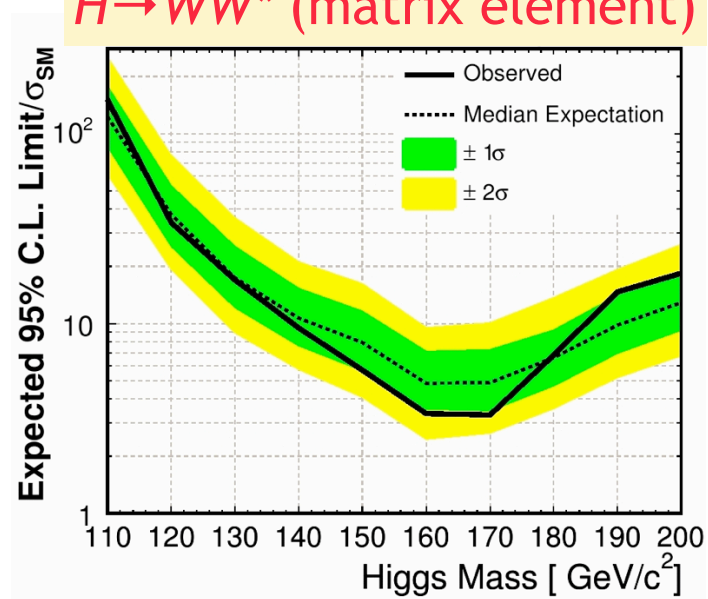


$HZ \rightarrow \ell\ell\nu\nu$



$H \rightarrow WW^*$ ($\Delta\phi$)

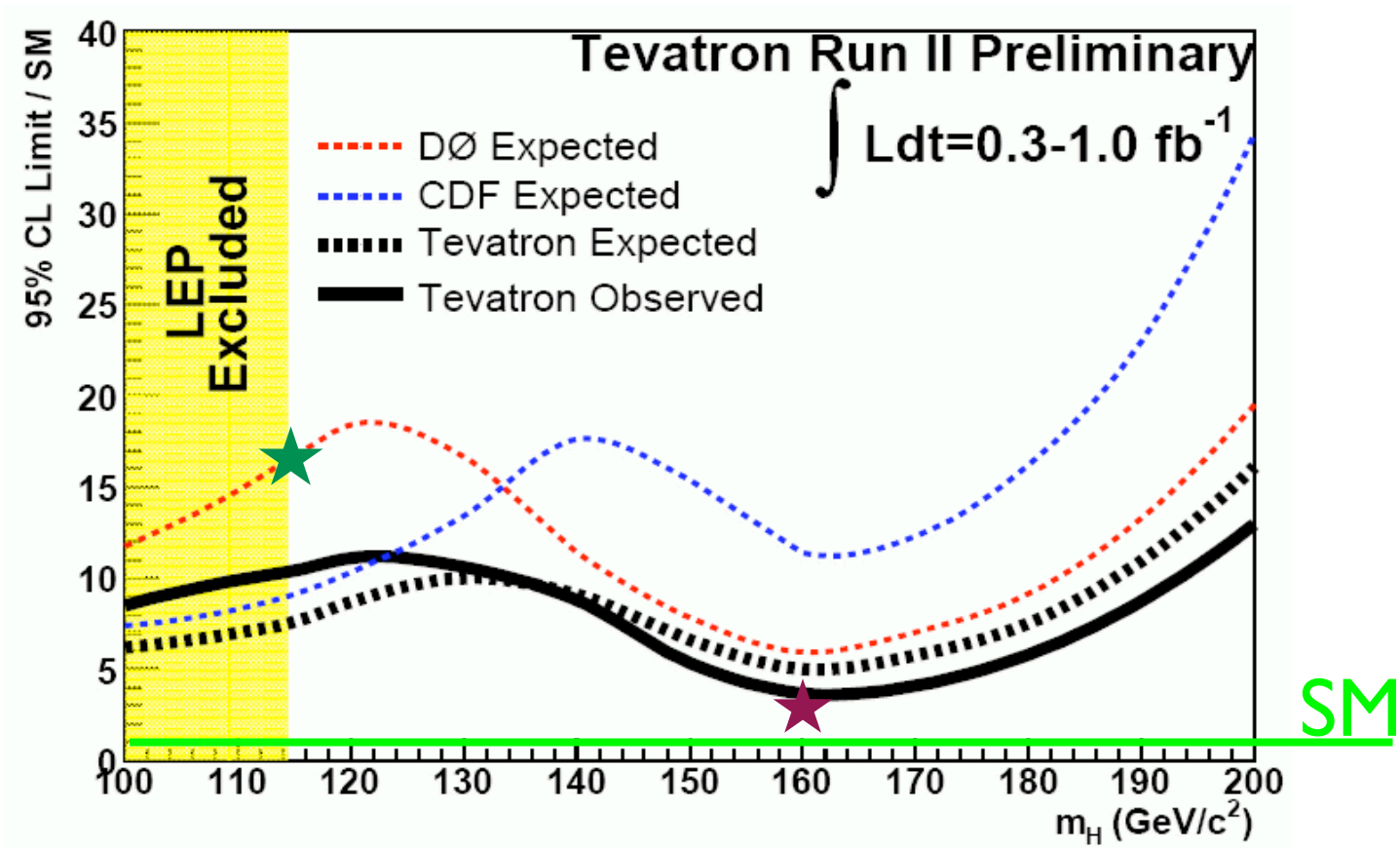
$H \rightarrow WW^*$ (matrix element)



- No hint of a Higgs signal … but we didn't expect to see one yet!

Tevatron Combination

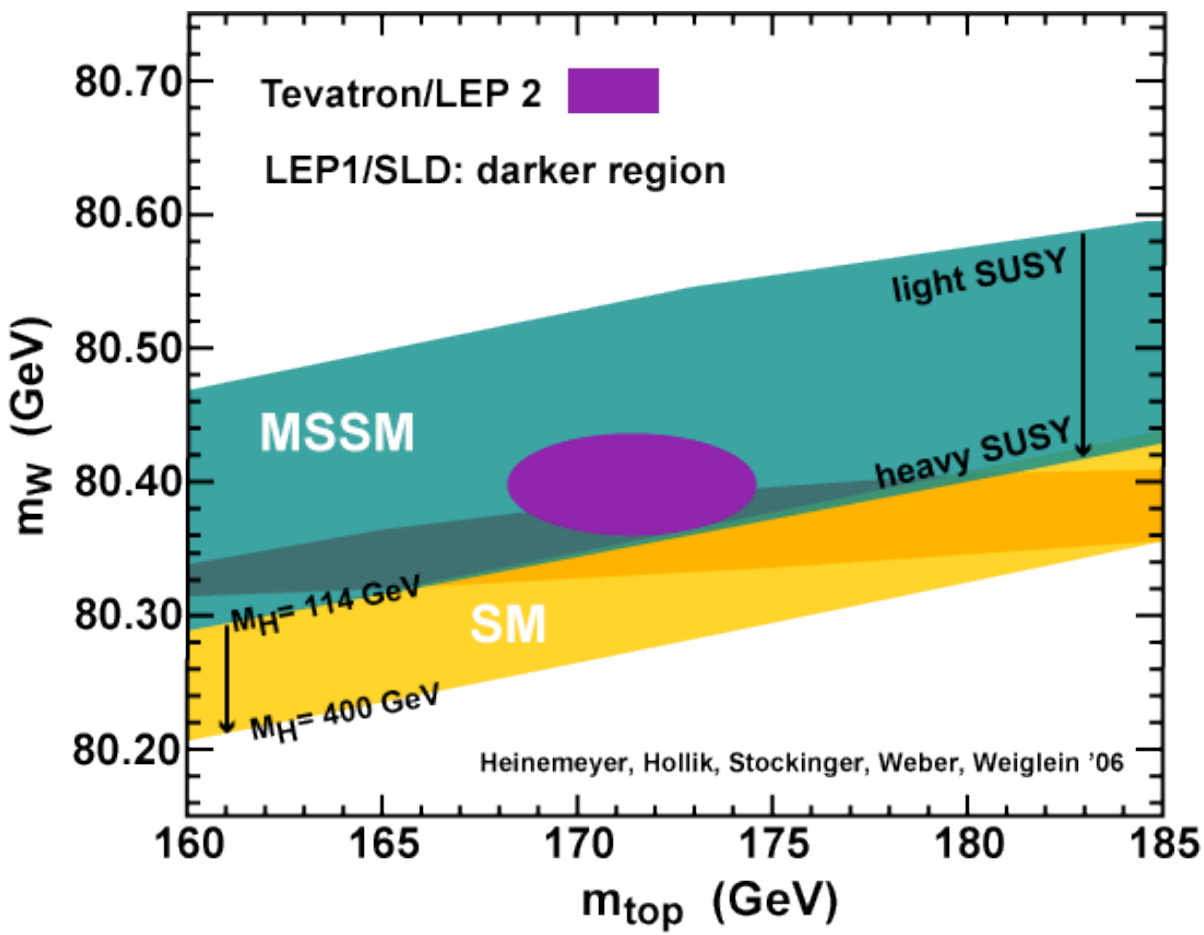
- Doesn't include all recent CDF measurements → further improvements very soon ★new $H \to WW$ measurements
  ★improved $ZH \to \ell^+\ell^-\nu\nu$



- H→*WW** contributes more at $m_H \approx 135 GeV/c^2$ than associated production!

Beyond the Standard Model Higgs

Precision measurements prefer minimal Supersymmetry (MSSM) to the SM

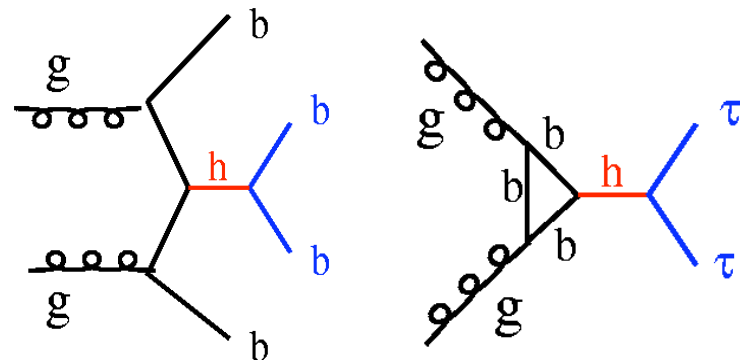


Non-SM Higgs Phenomology

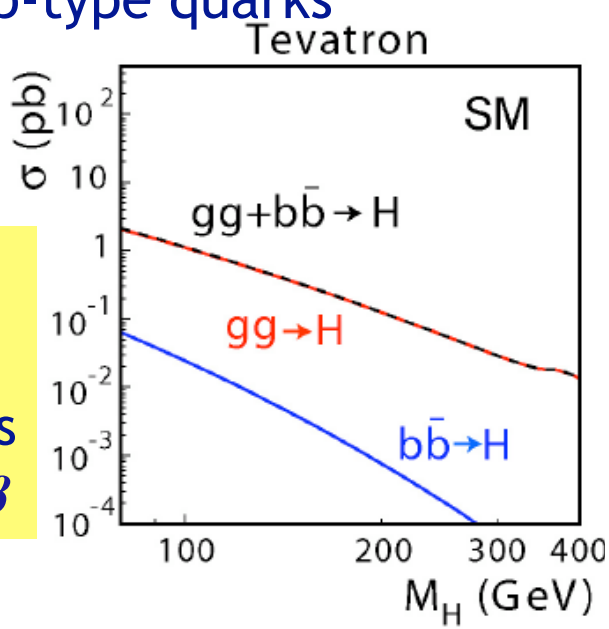
Supersymmetry (and other Beyond the Standard Models) requires 2 Higgs doublets

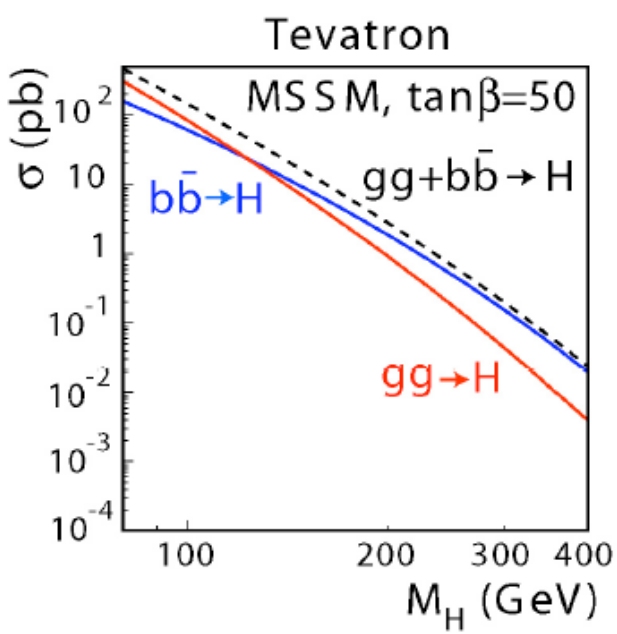
$$\mathcal{L} = m_{\mathrm{d}} \, (u,d)_L \begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix} d_R + m_{\mathrm{u}} \, (u,d)_L \begin{pmatrix} v\sin\beta \\ 0 \end{pmatrix} u_R$$

- Four physical Higgs bosons h^0, A^0, H^0, $H^{\pm}$
- parameterised by β and $v = 246$ GeV
- One doublet gives mass to down-type quarks and charged leptons
- One doublet gives mass to up-type quarks



- Production of light Higgs enhanced by ~**tanβ**
- Production of down-type quarks and leptons enhanced by ~**tanβ**





$H \rightarrow \tau^+\tau^-$ Search

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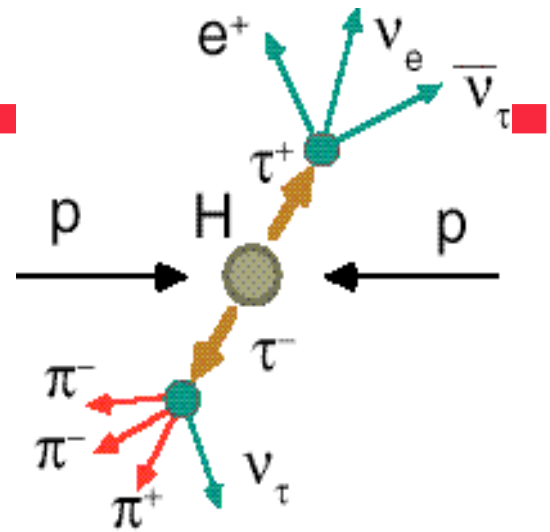
- Event Selection
  - 1 hadronic tau decay and 1 $\tau \rightarrow \ell\, \nu_\tau \bar{\nu}_\ell$ decay **BR=46%**
  - 2 $\tau \rightarrow \ell\, \nu_\tau \bar{\nu}_\ell$ decays **BR=6%**



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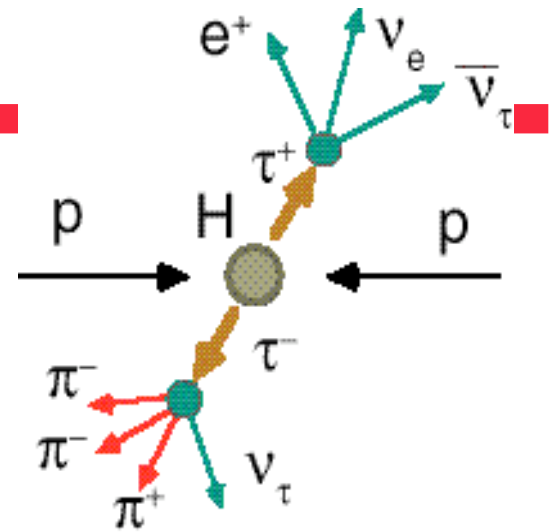

- Hadronic tau selection most challenging:
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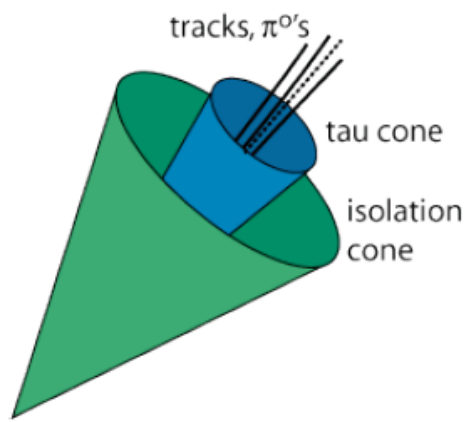
  - No activity in "isolation cone" around narrow signal cone
  - 0.1–1% of jets are misidentified as tau's



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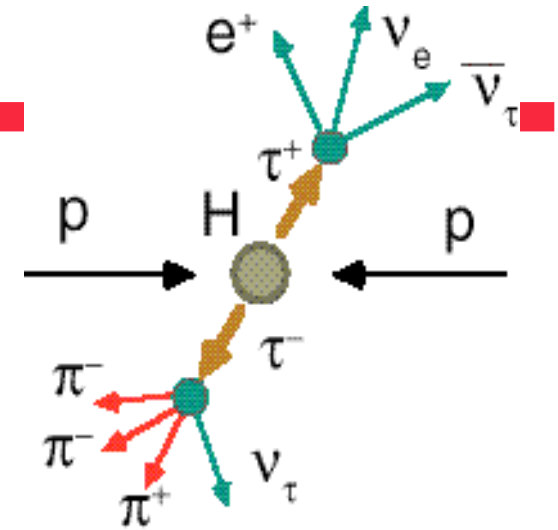

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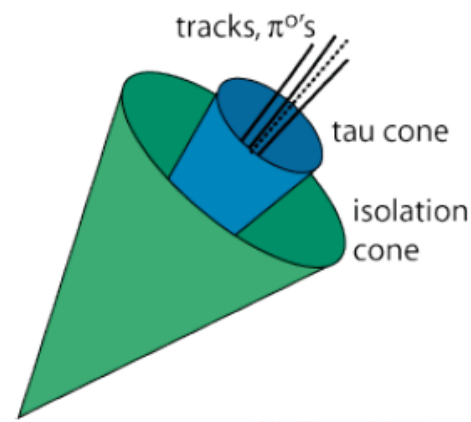
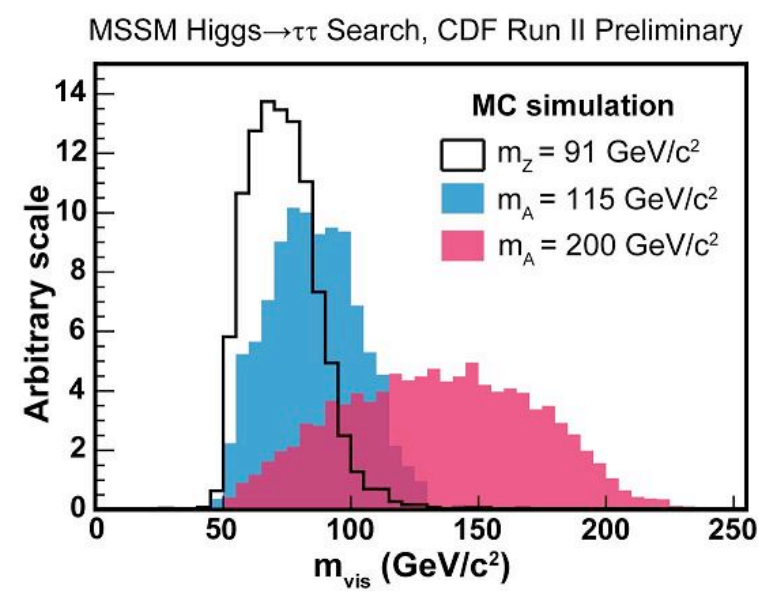
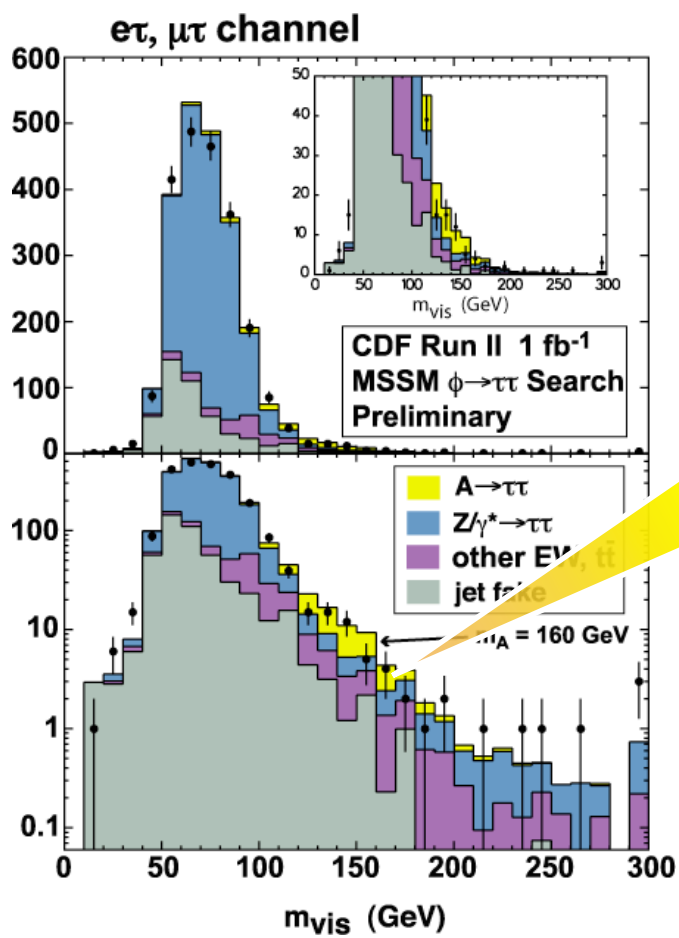


- Full mass reconstruction not possible
  - Use "visible mass": invariant mass of visible τ decay products and $\not\!\!E_T$
  - Acceptance 1.1% at m_H = 90 GeV/c^2
  - Acceptance 3.3% at m_H = 250 GeV/c^2

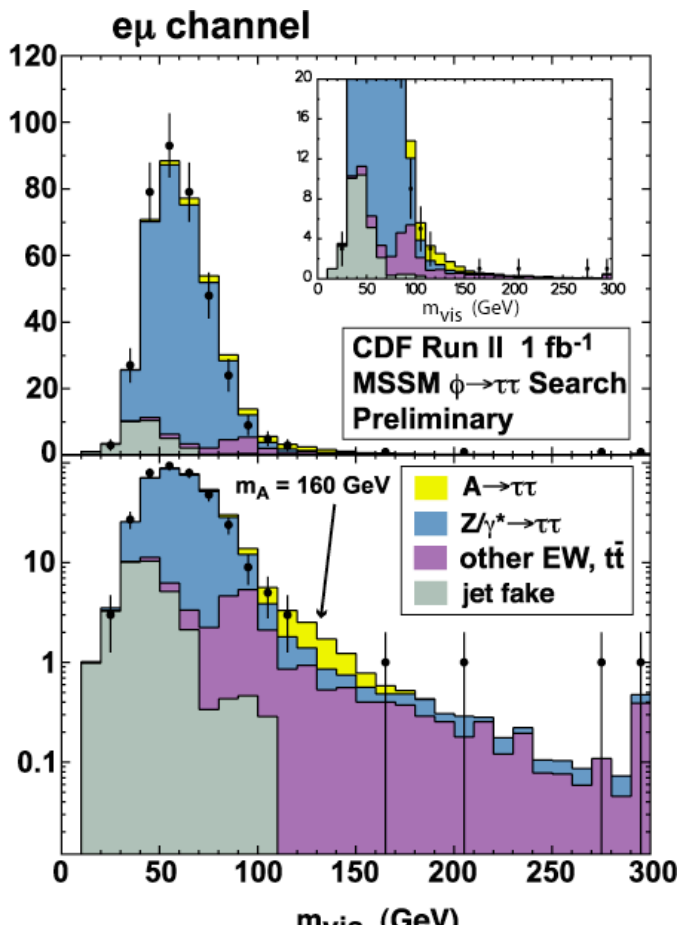


$H \rightarrow \tau^+\tau^-$ Visible Mass Distribution

- Analysis was blinded → visible mass distribution not looked at until all background and acceptance finalised



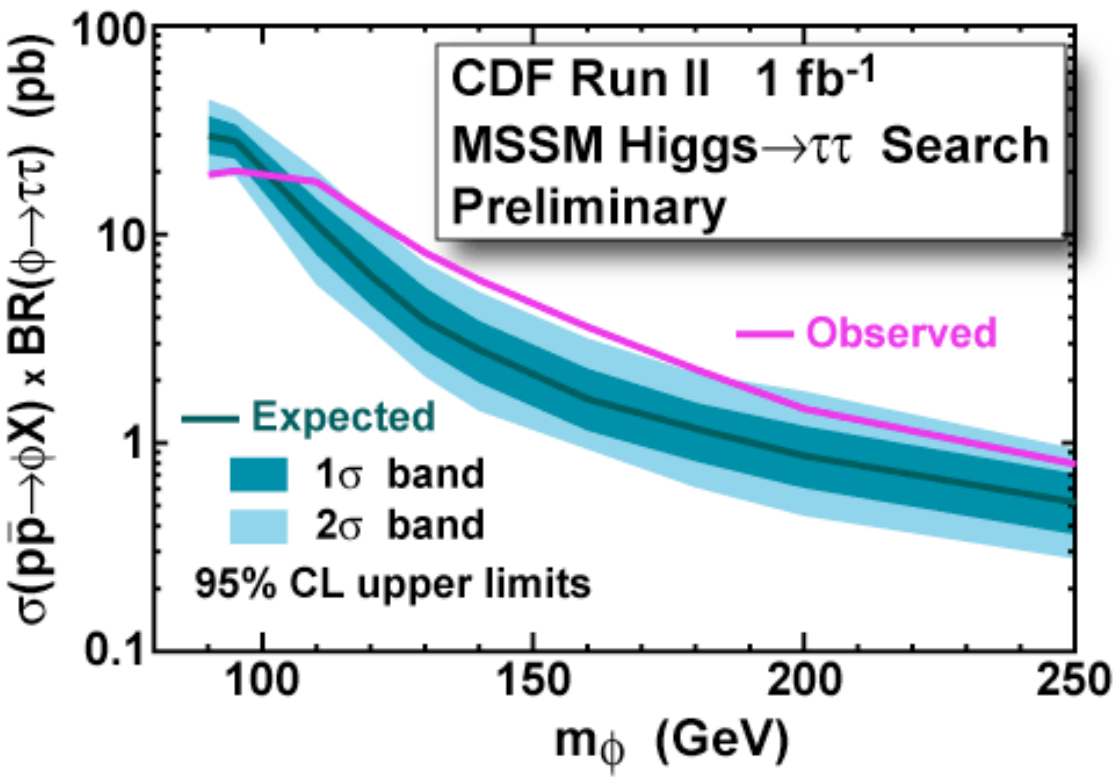
Surprise!
Little bump
at 140 GeV/c^2

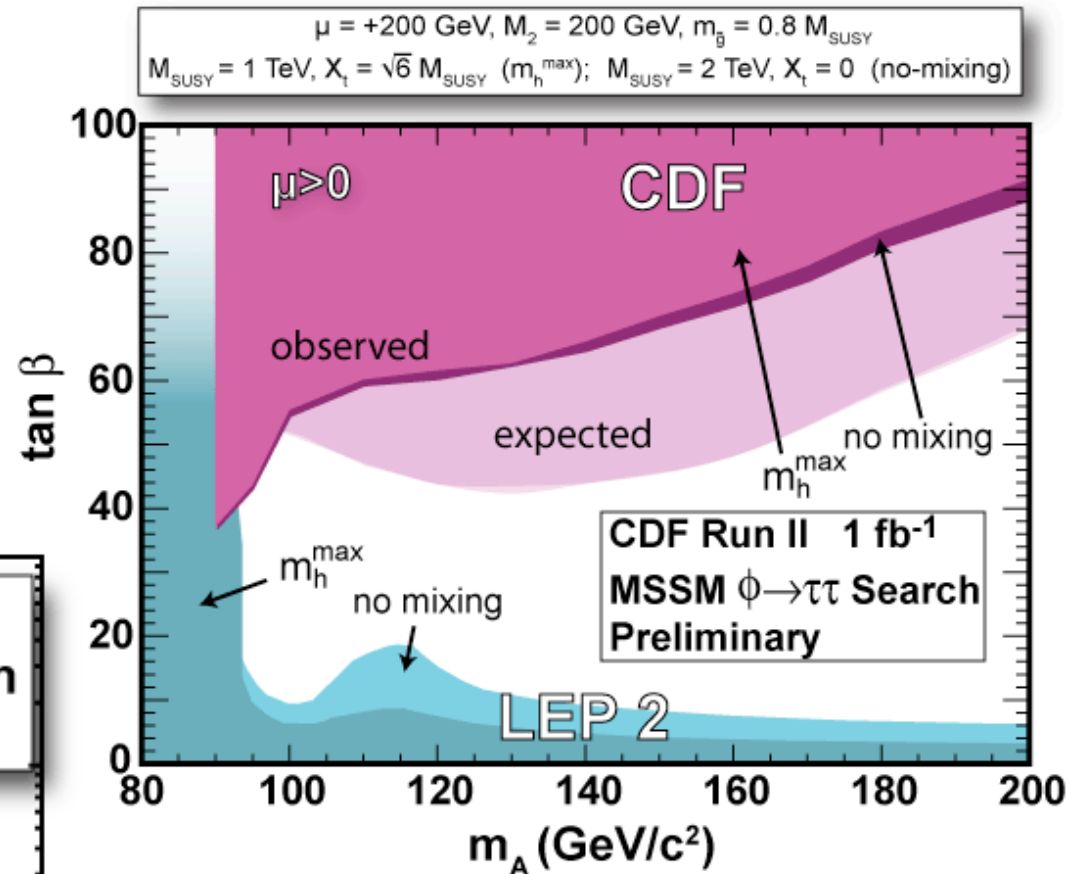


- Data mass distribution agrees with SM expectation, mostly.
- Slight excess has a significance of 2.1σ (cross section ~2 pb)

MSSM Limits

- Mass bump is not enough to claim discovery → limits set on MSSM parameters.

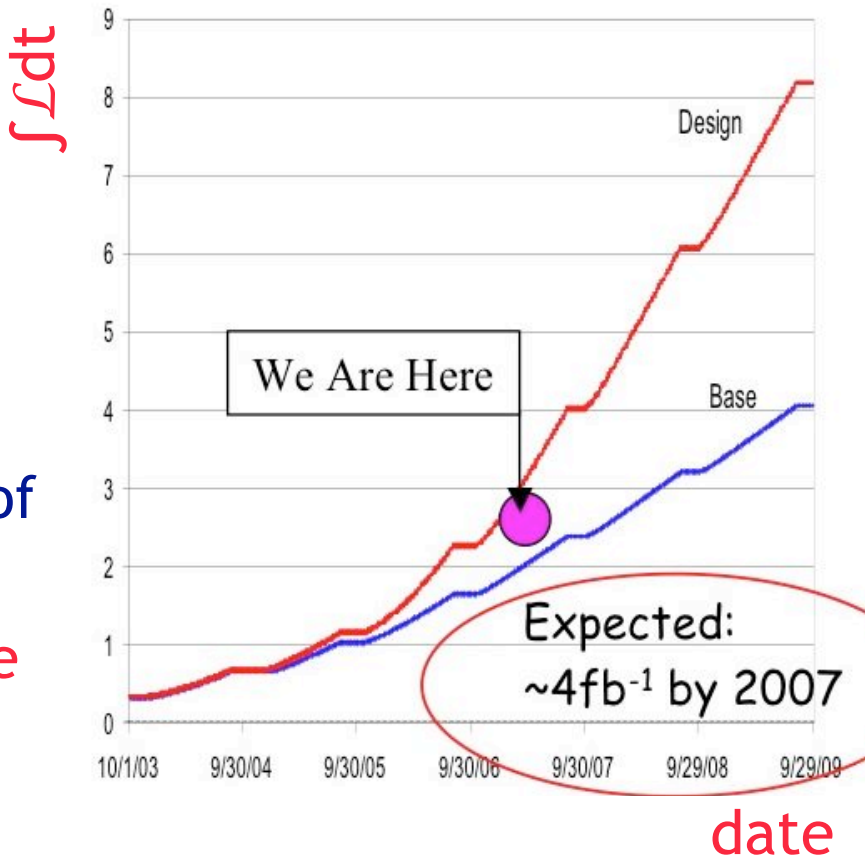




Conclusions & Outlook

- Recent improvements in:
  - ➡ *b*-tagging, di-jet mass resolution
  - ➡ lepton acceptance, triggers
  - ➡ analysis techniques

  have been critical to improving sensitivity of **direct Higgs searches**
- Precision measurements m_W and m_t improve **indirect Higgs search**
- Further improvements and factor of **2.5 more luminosity** for direct searches are currently being incorporated.



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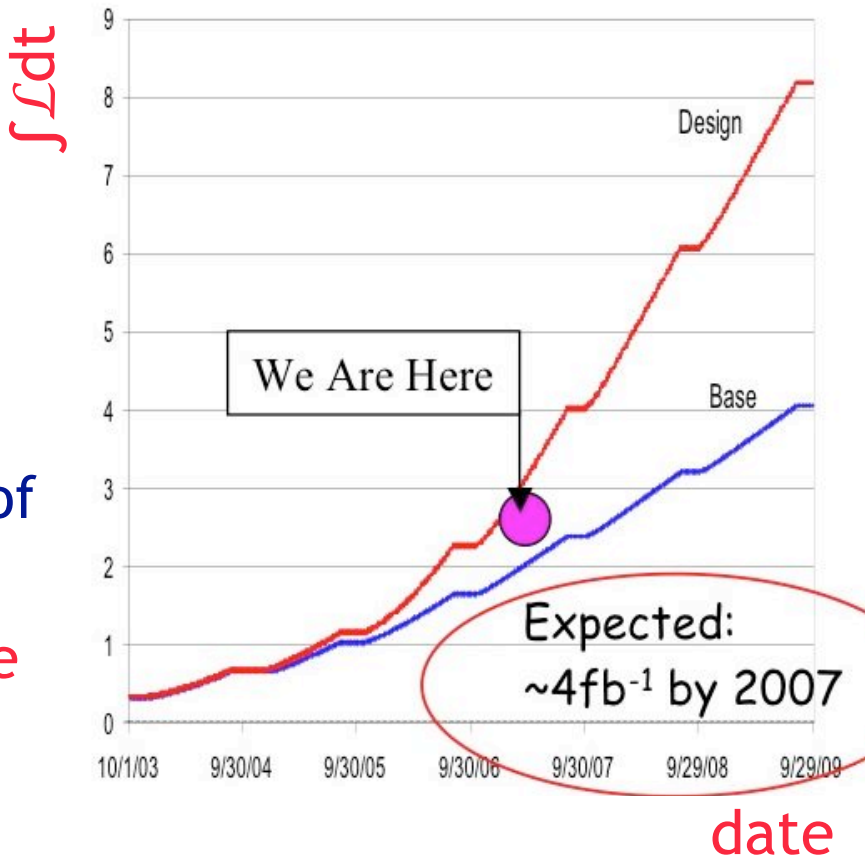
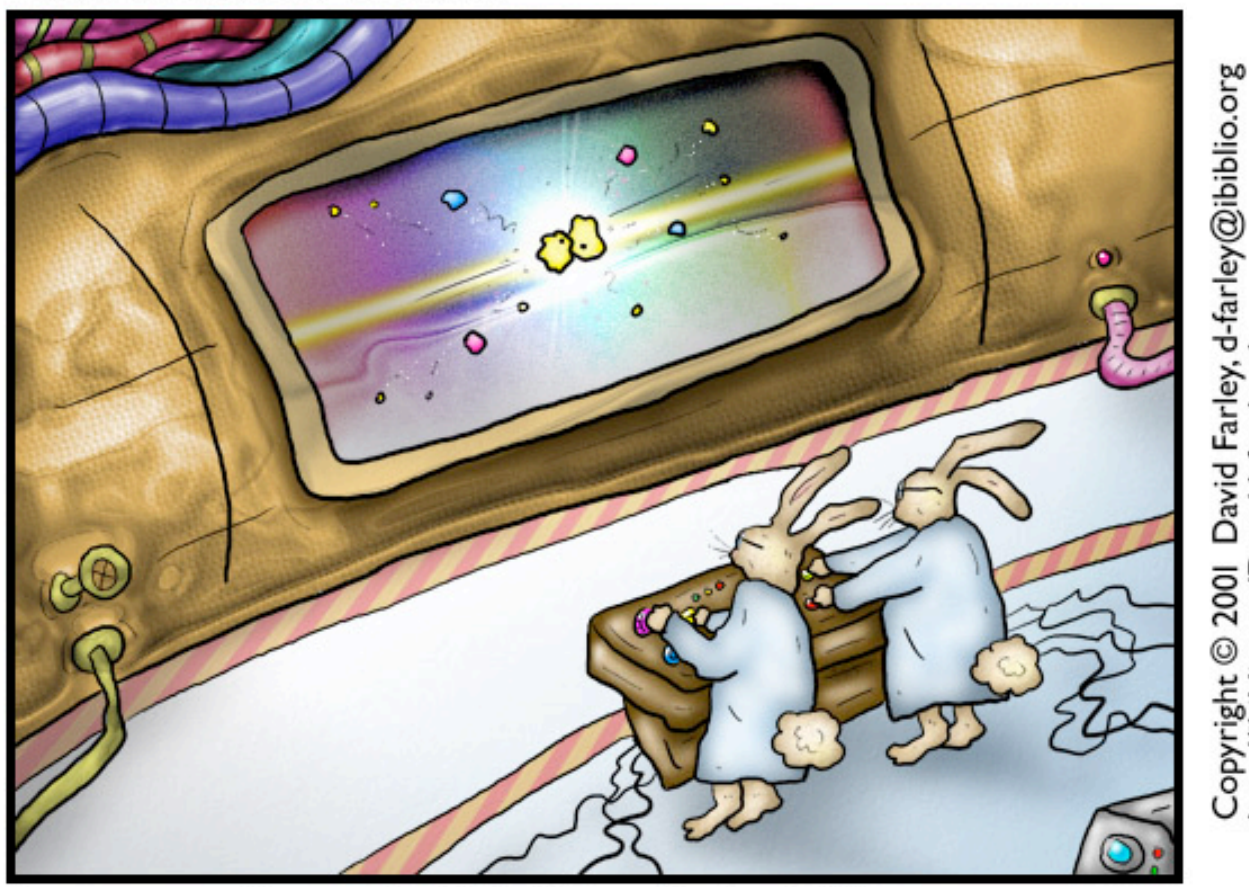


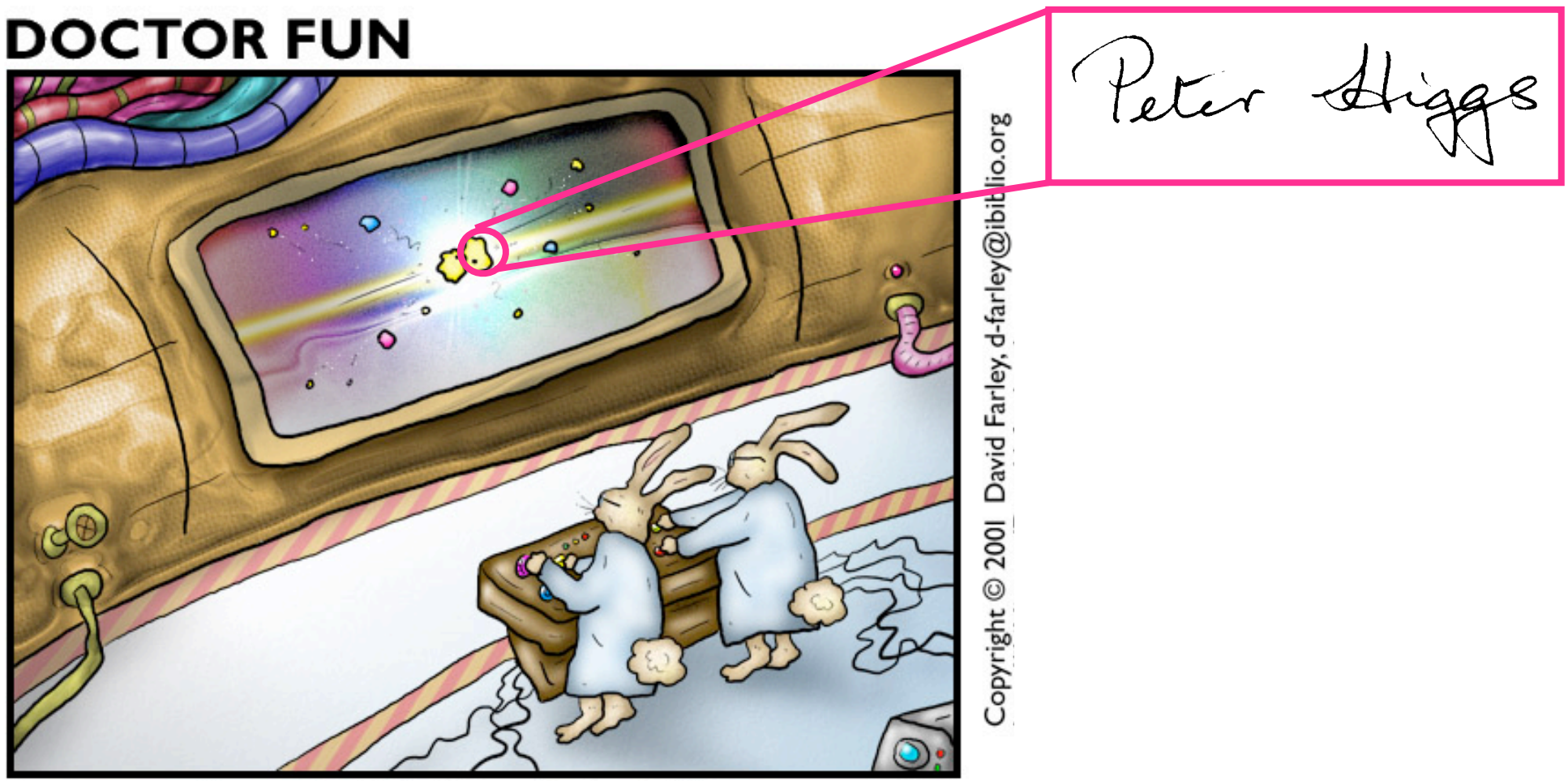
- The Tevatron does have a chance to find the SM Higgs! **Continued luminosity improvements** and **collaboration between CDF & DØ will be essential!**

Let’s dream…

- 

Bunny researchers at the High Energy Candy Collider generate exotic short-lived isotopes of Peeponium.

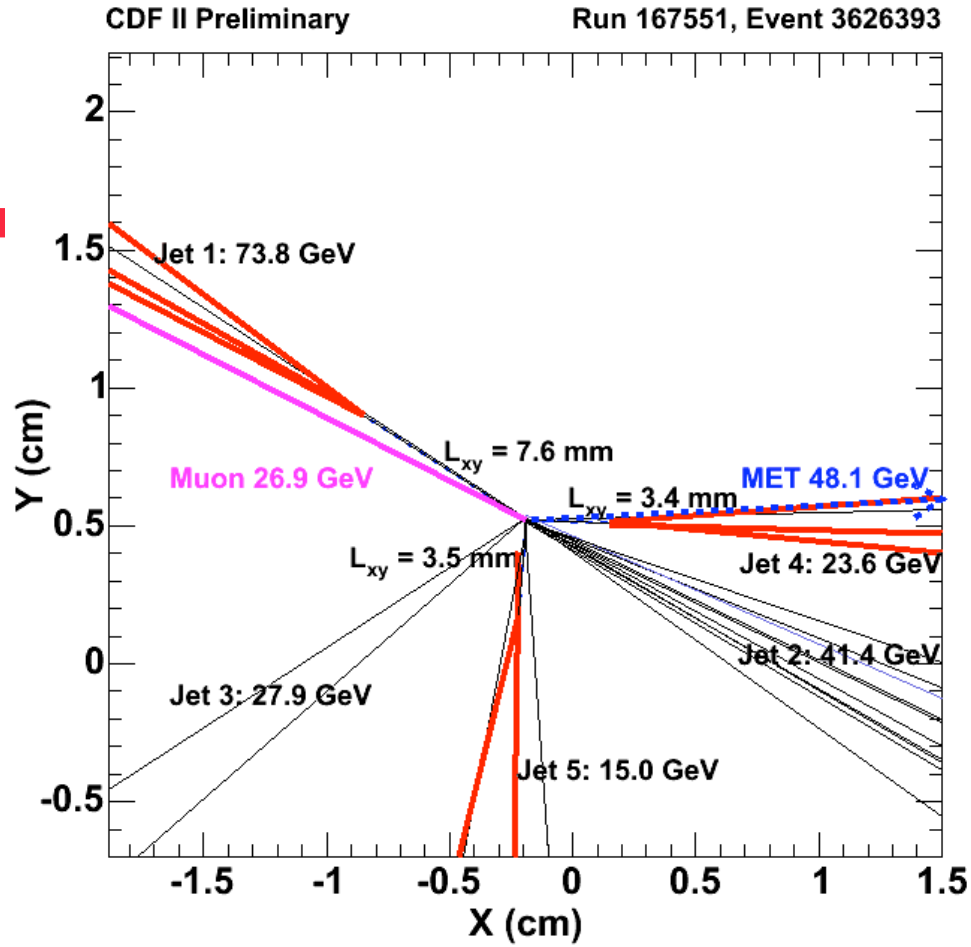
Let's dream…

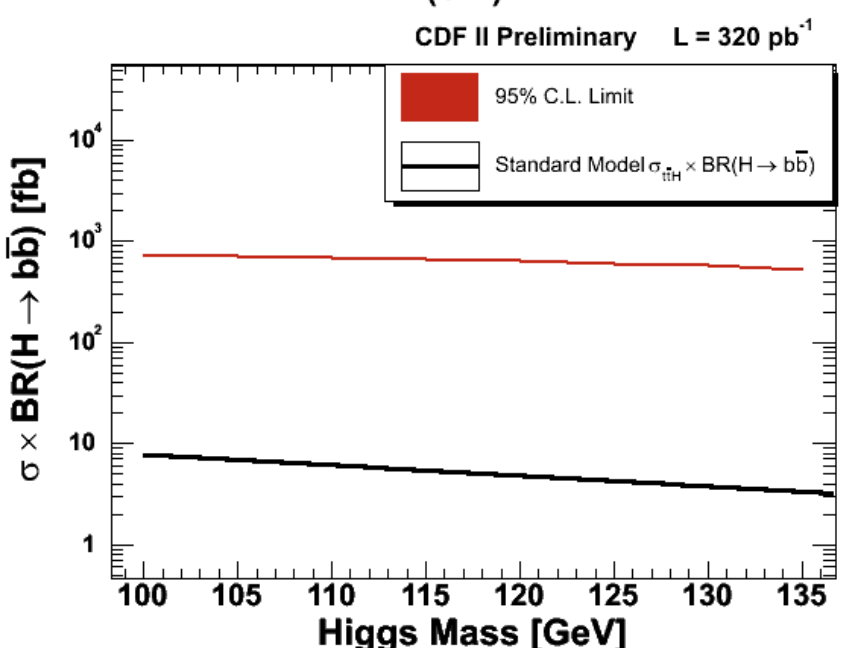

DOCTOR FUN
Peter Higgs
Copyright © 2001 David Farley, d-farley@ibiblio.org
Bunny researchers at the High Energy Candy Collider generate exotic short-lived isotopes of Peeponium.

Backups

$ttH \rightarrow bbbbWW$

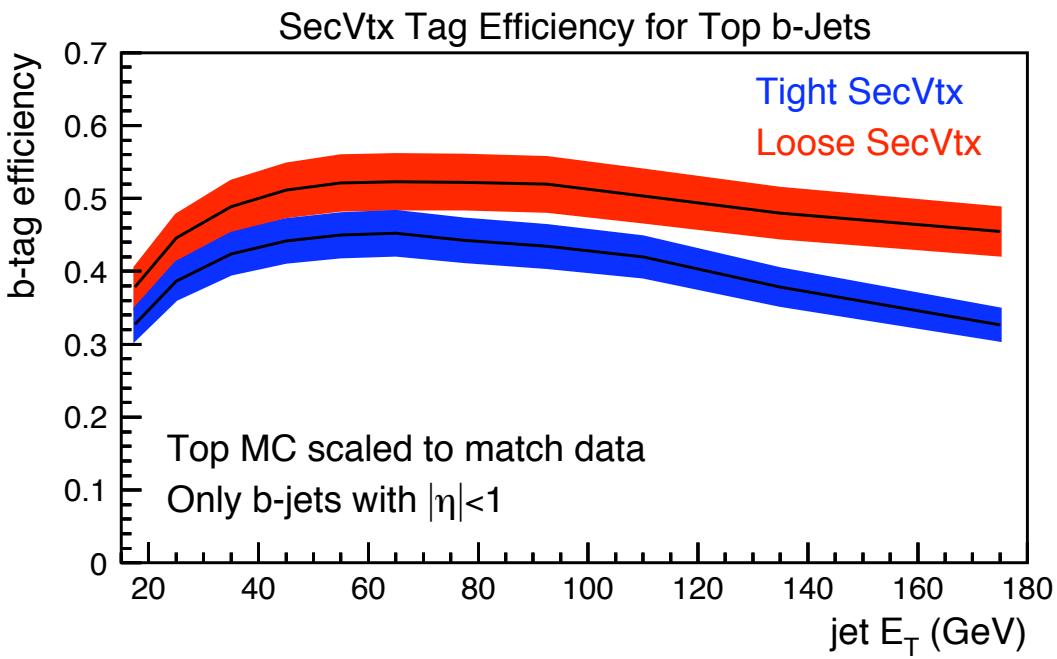
- 1 lepton, ≥4 jets, missing-E_T
- ≥ 3 *b*-tags
- **1 event found in 320 pb^{-1}**

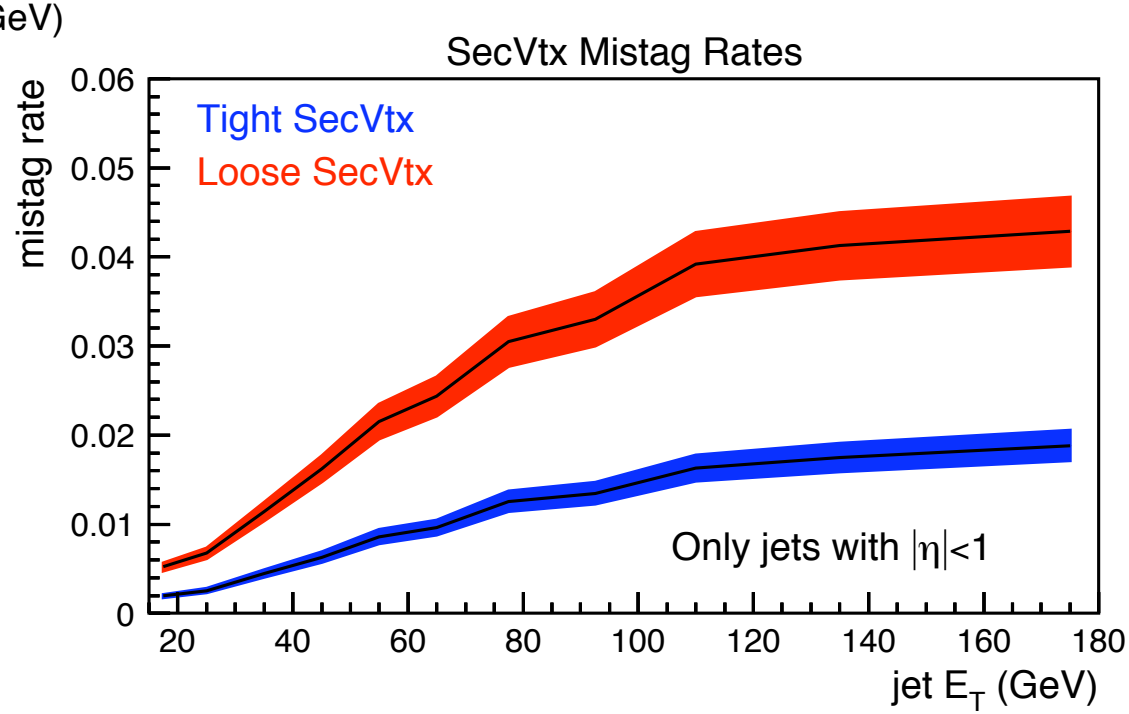




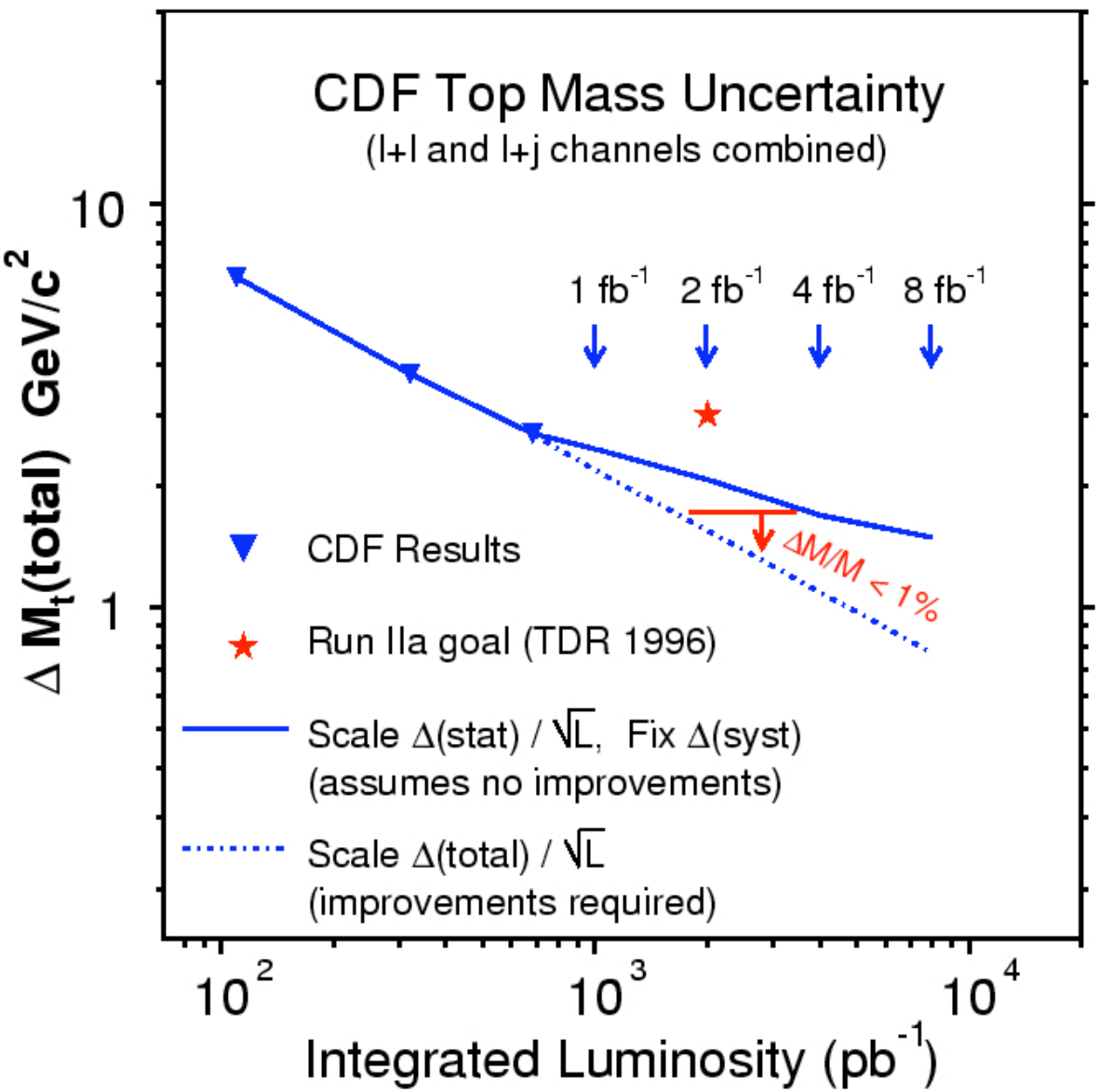
Limit: σ(obsv)/σ(SM) < 168 for m_H=115 GeV

b-Tagging Efficiency & Mistags





Top Mass Prospects



Reminder: Hadron Collider Dynamics

- On an event-by-event basis we don't know the energy of the hard collision
  - ➡ *We must reconstruct the mass of the Higgs boson directly.*
  - ➡ *Only possible for some channels.*

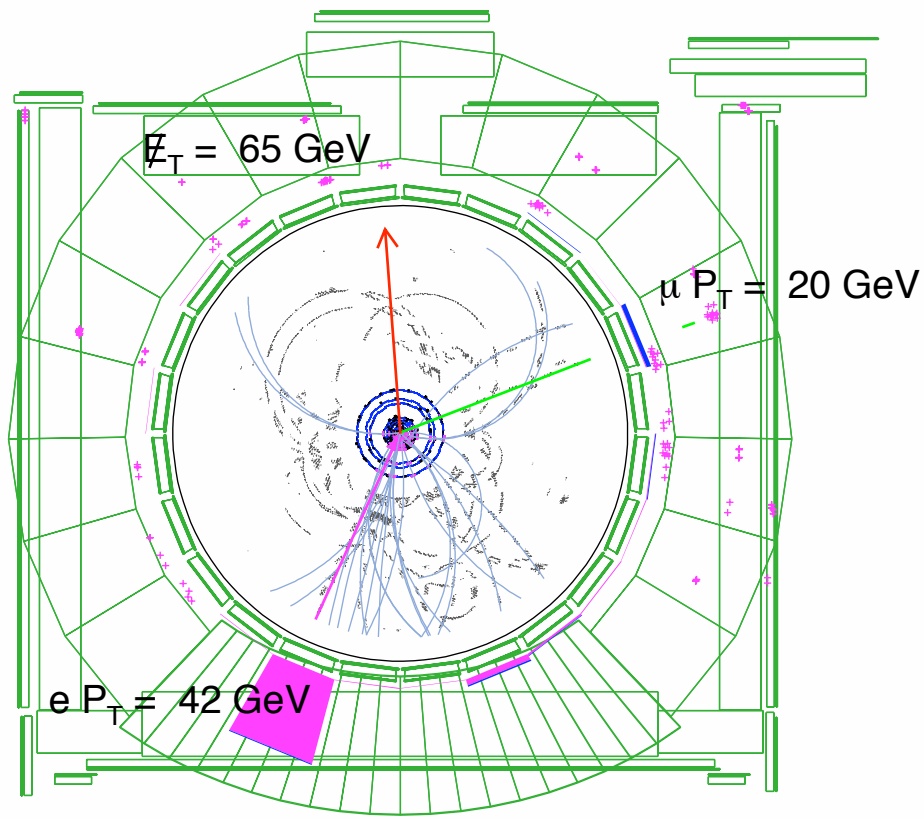
- The colliding partons have very small momentum transverse to beam.
- We detect all interactions transverse to the beam
  - Use the component of track **momentum** transverse to beam:

$$p_T = \sqrt{p_x^2 + p_y^2}$$

  - Resolve calorimeter energy into transverse component

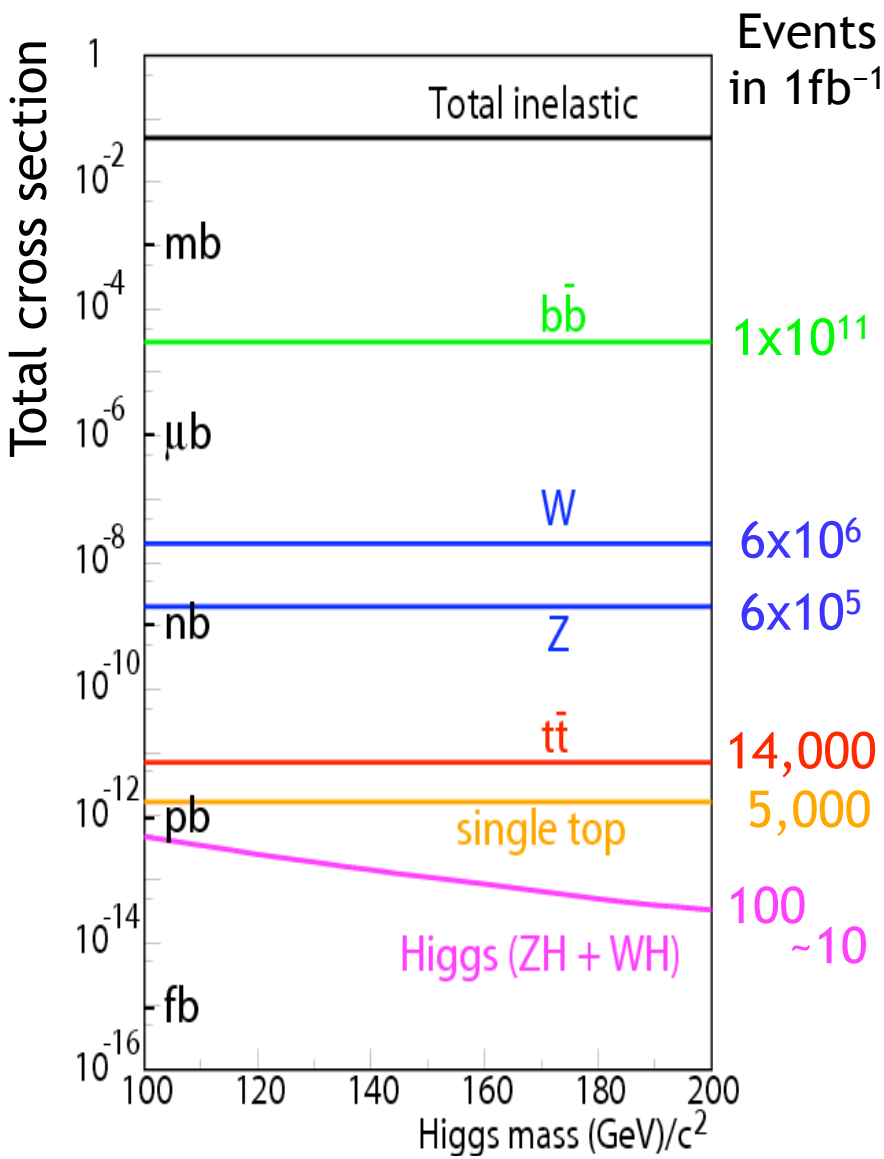
$$E_T = E\cos\theta$$

- Any missing "transverse momentum" is attributed to invisible particles $\not{E}_T$



W^+W^- candidate event

The Cross Section Challenge



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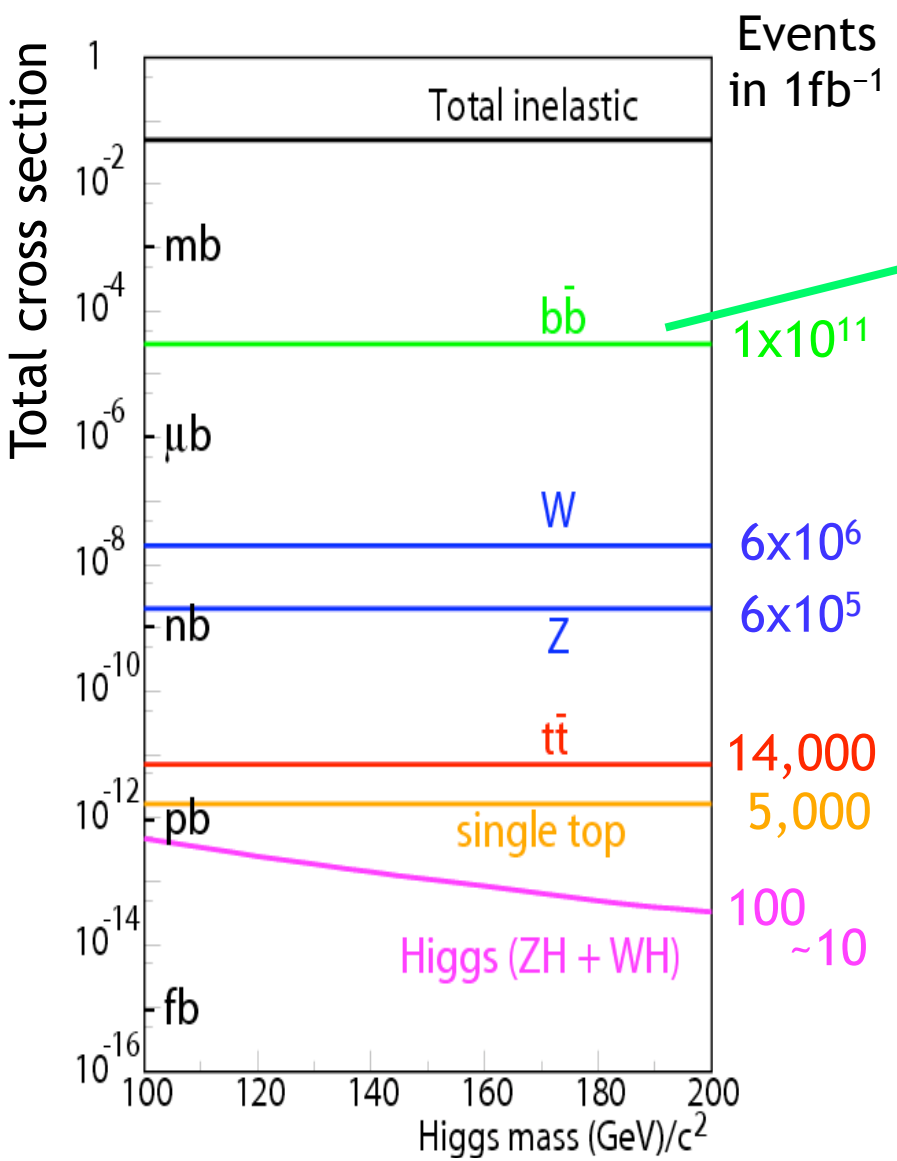

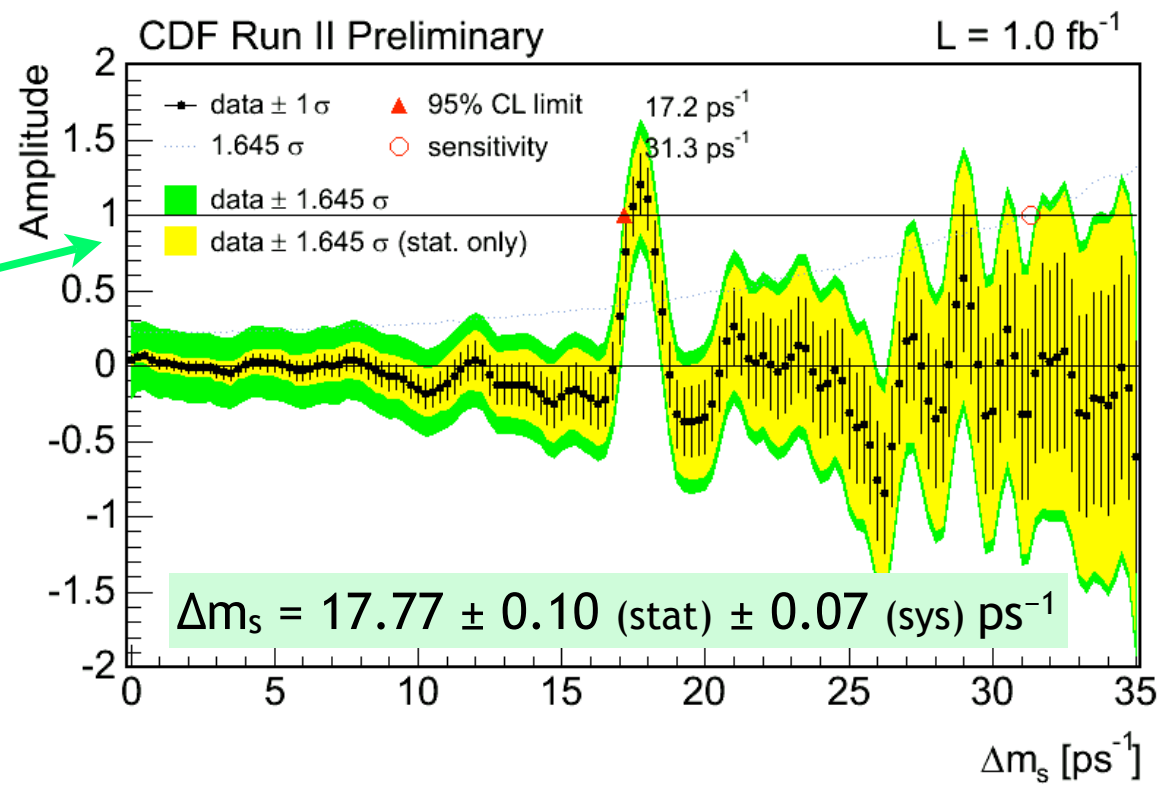

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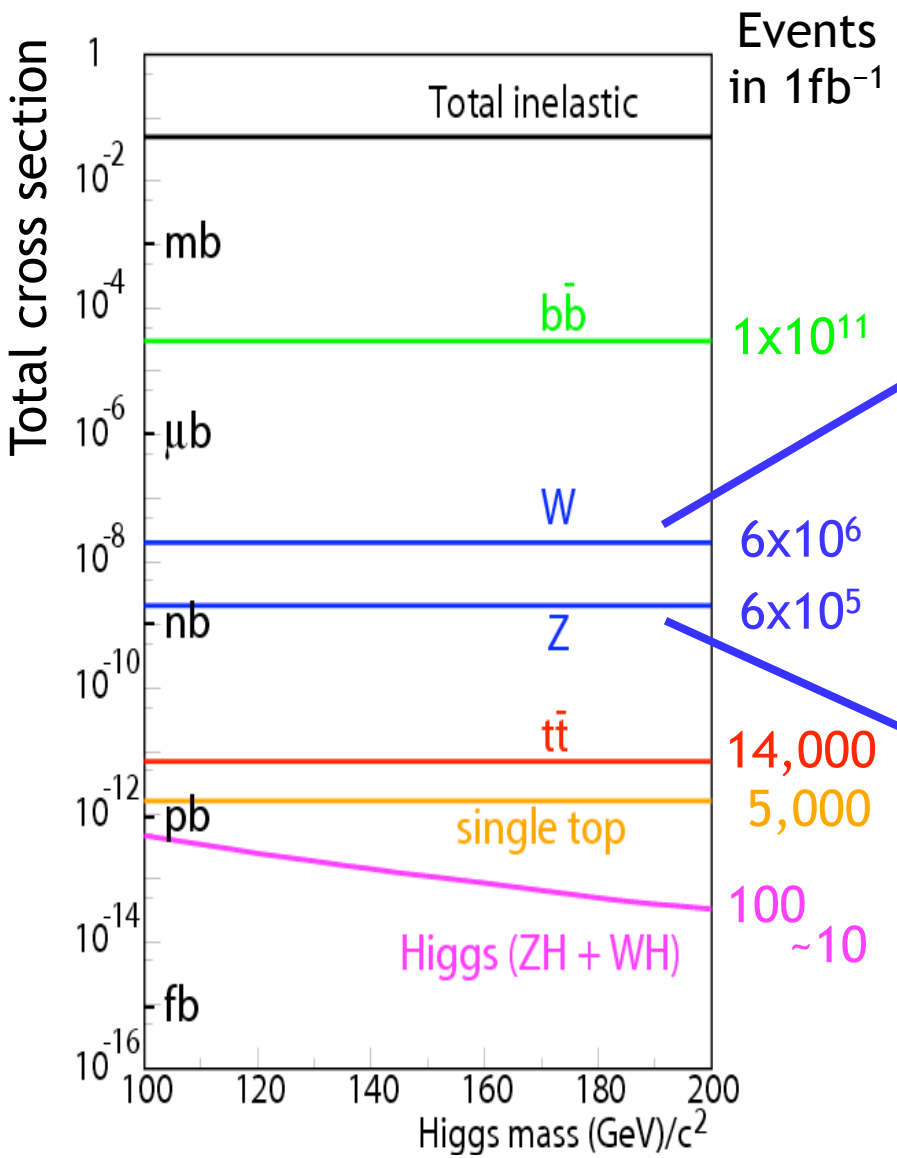
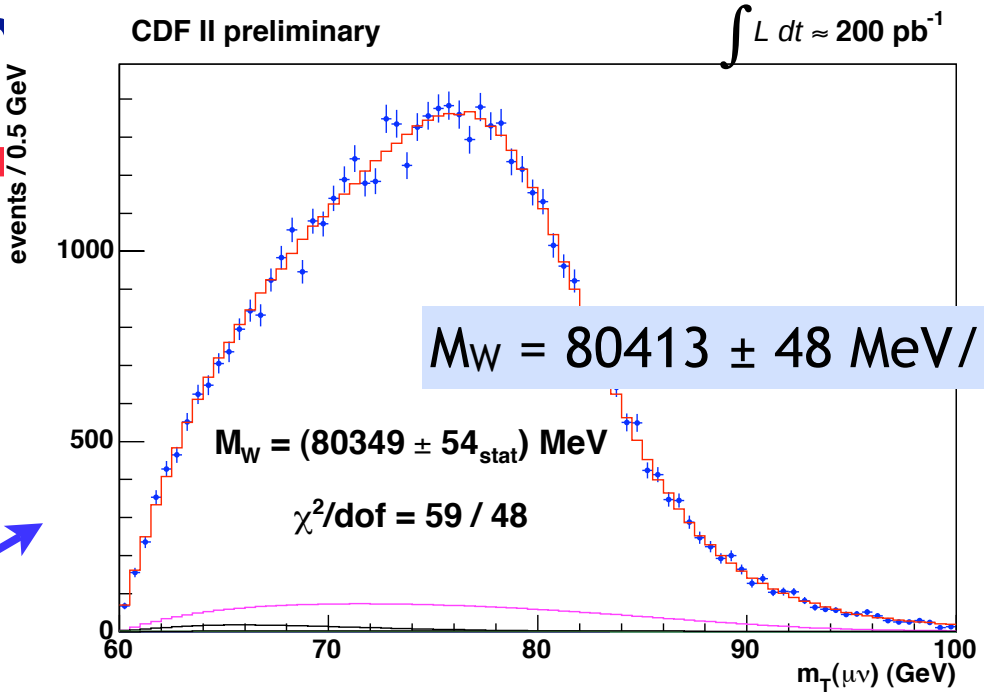
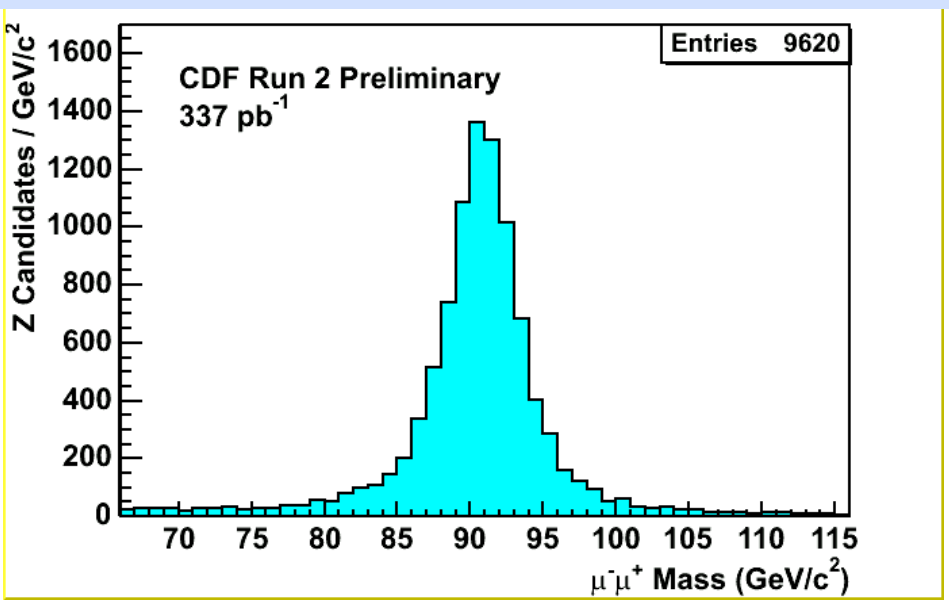




$M_W = 80413 \pm 48$ MeV/c^2

$\sigma(p\bar{p} \rightarrow Z) = 261.2 \pm 2.7(\text{stat})\ ^{+5.8}_{-6.9}(\text{sys}) \pm 15.1(\text{lum})$ pb



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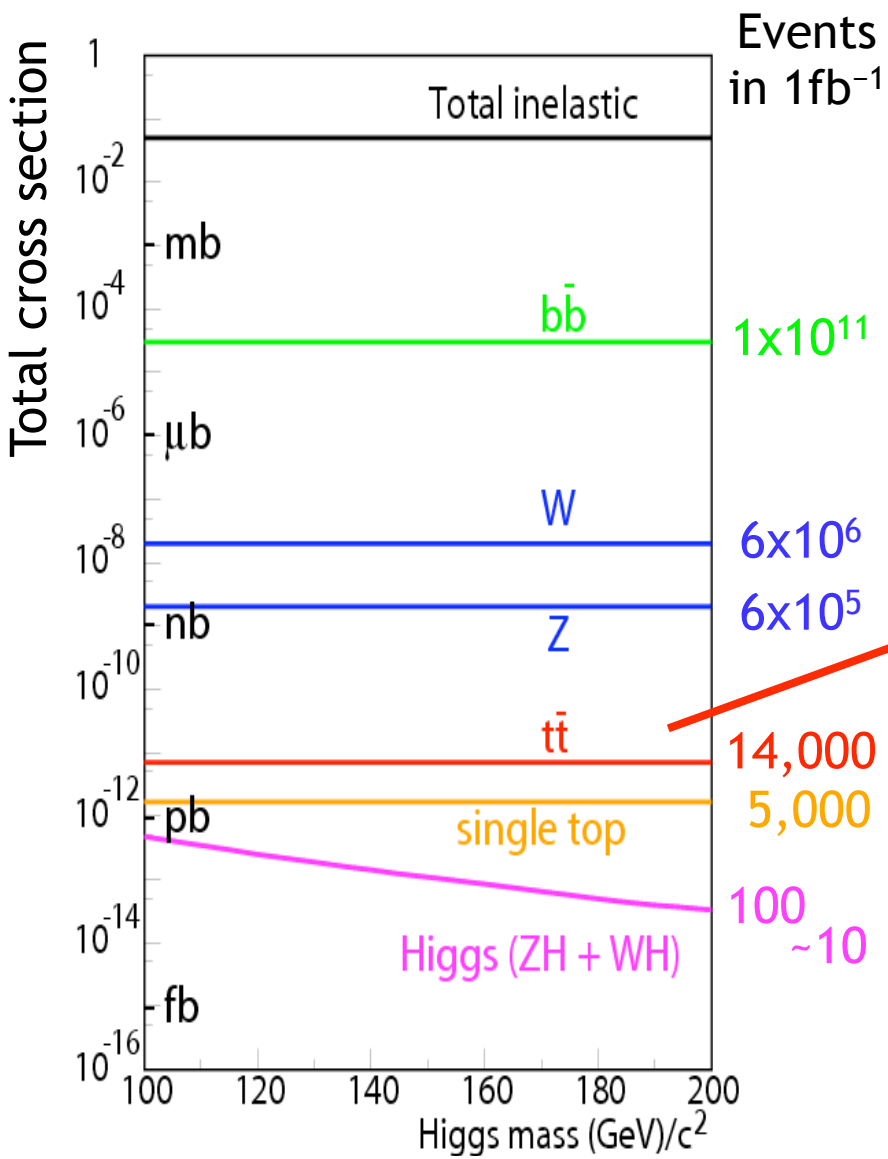

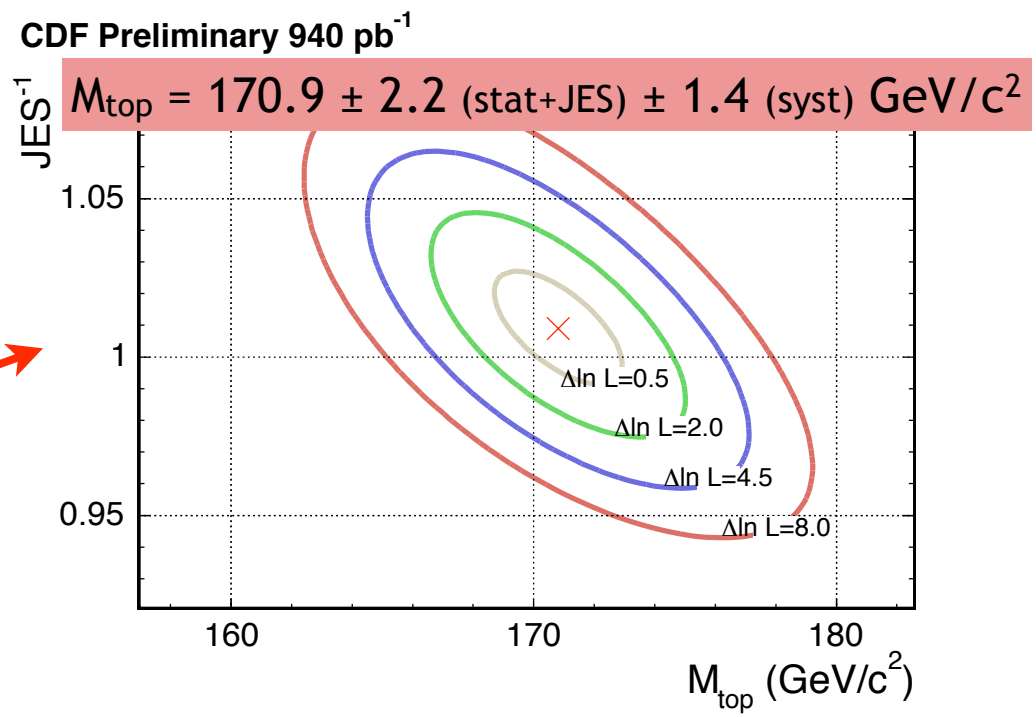

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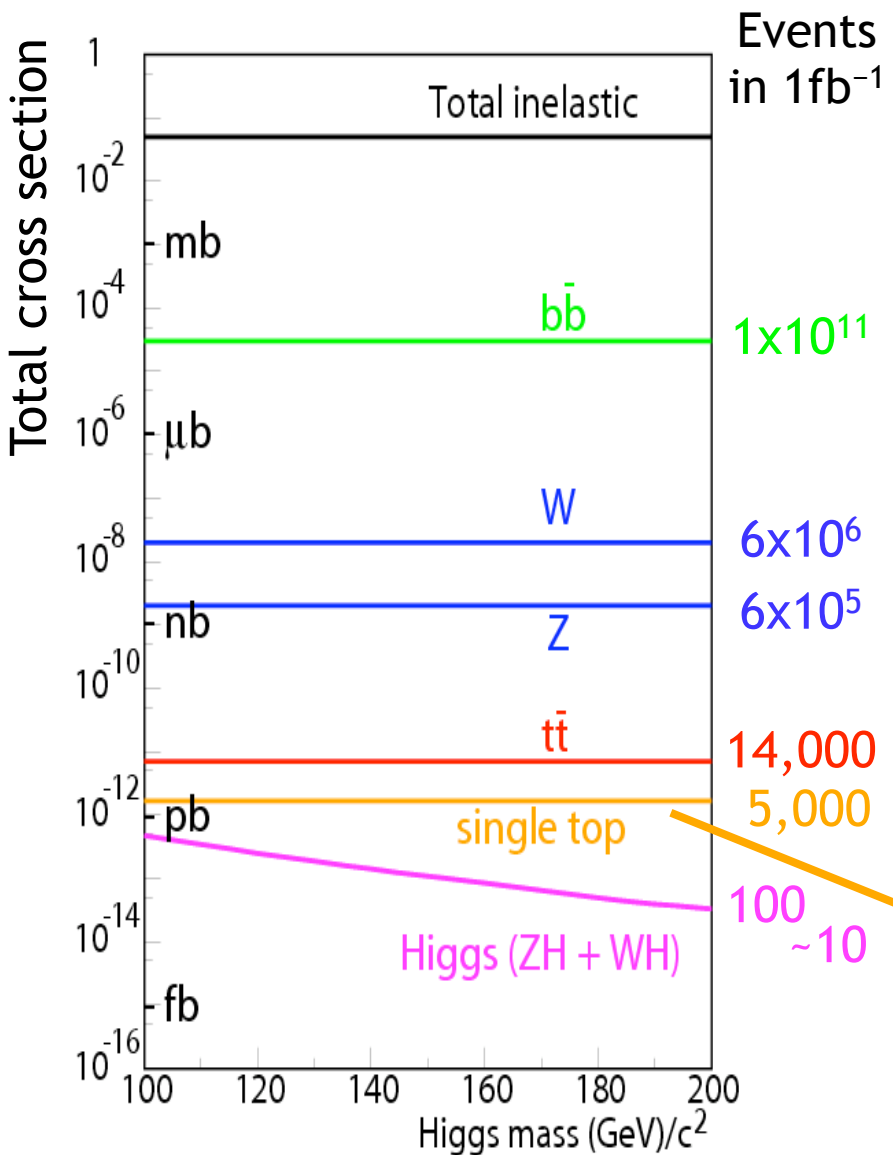

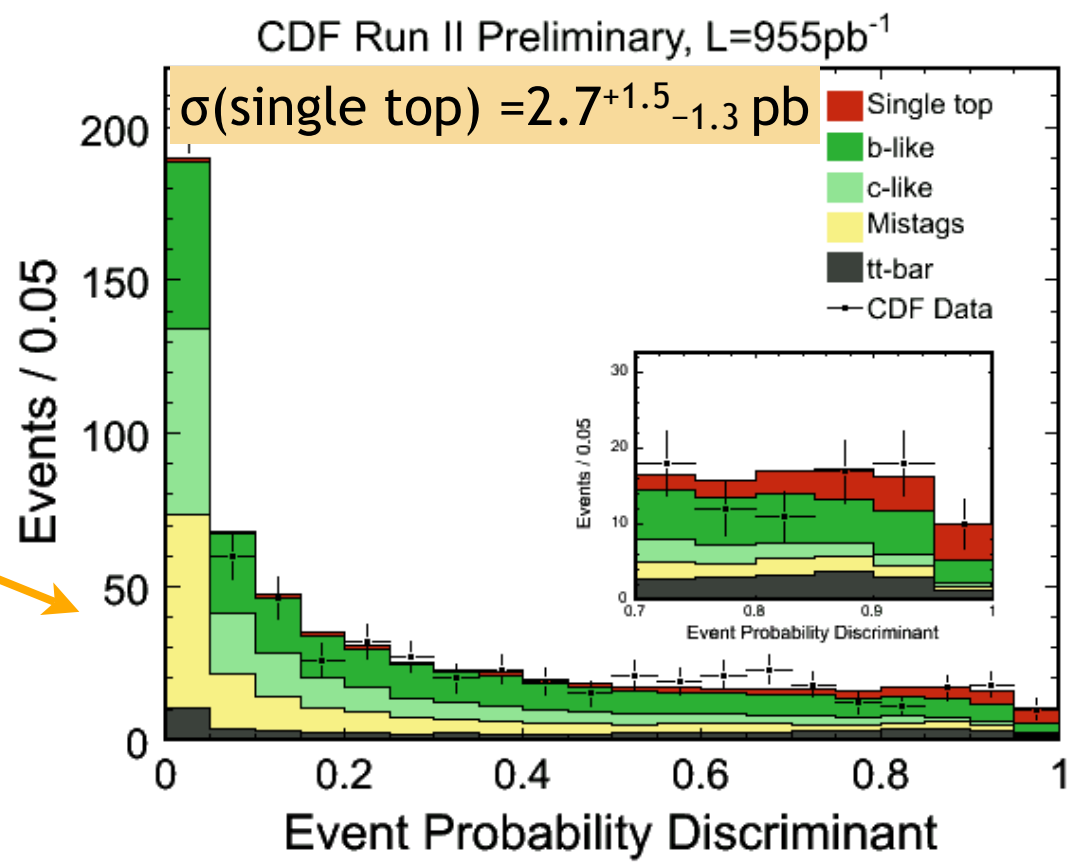

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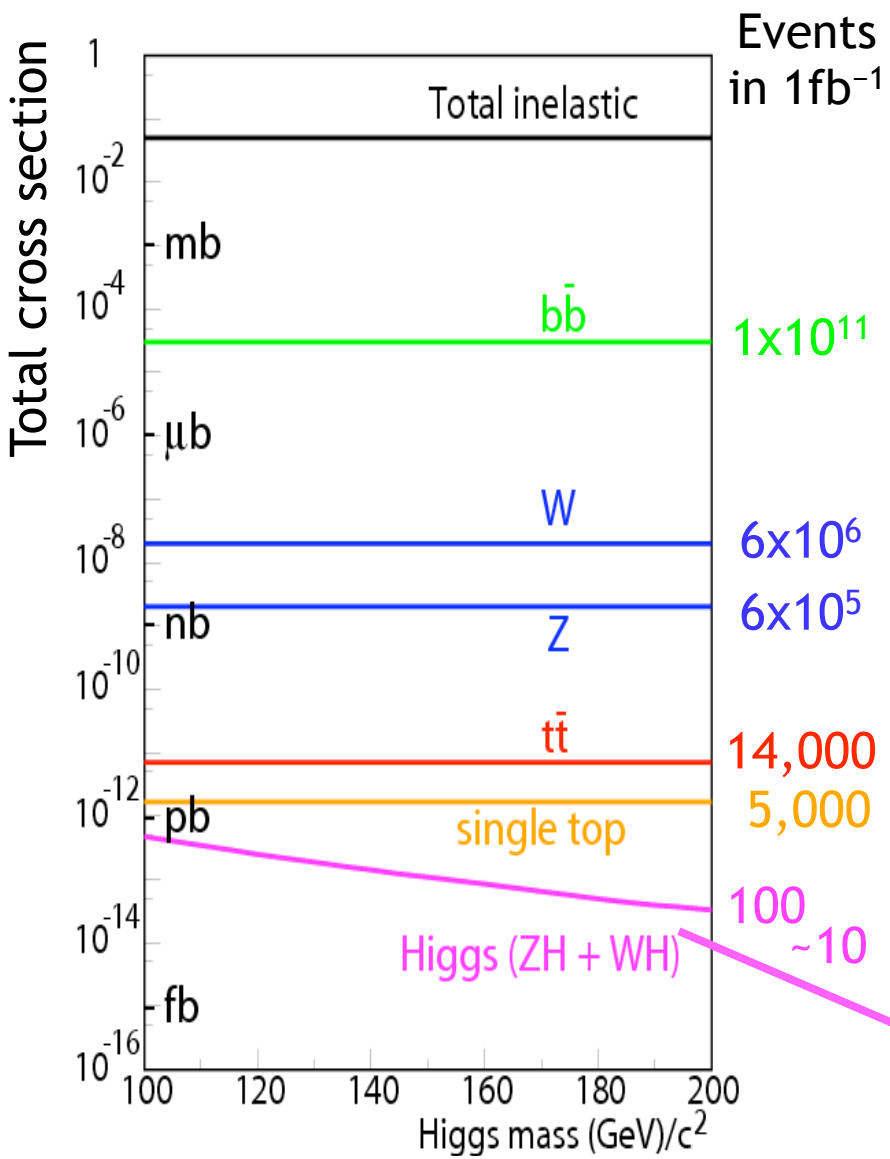

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